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Synthetic Vision Technology Demonstration

Volume 1 of 4

Executive Summary

Malcolm A. Burgess, FAA
Terence Chang, TRW
Dale E. Dunford, USAF
Roger H. Hoh, Hoh Aeronautics
Walter F. Home, GTRI
Richard F. Tucker, TRW

Synthetic Vision Program Office
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approach, with seconds to touchdown, and during a high workload phase of flight. This transition from "head down" to "head up" would be avoided if the pilot could already "see" the runway and flight data on a headup display throughout the approach, in spite of fog and precipitation.

The concept of using millimeter-wave sensors for low visibility aircraft operations is not new. In the late 1960's, an imaging 33 GHz radar designed by Texas Instruments was flight tested on a Convair 240 aircraft with the image generated on a head-down cathode ray tube display. The weather penetration capability of the radar was demonstrated in fog, snow, and light rain. Swissair conducted flight tests with a different configuration of the TI system in the early 1970's. It was later installed by the Air Force Flight Dynamics Directorate on a C-135 aircraft with a five foot antenna for flight evaluation. The Air Force flew 1,619 approaches in a wide variety of weather-conditions, including heavy snow and heavy rain, further validating the weather penetration capability of the millimeter-wave radar.

In the early 1980's, Federal Express Corporation pioneered the development of the HUD as the display device to be used with an imaging, weather penetrating sensor. Considerable effort and investment led to the certification of a HUD for commercial aviation use. However, the risk and estimated additional cost of further development, to include a weather penetrating sensor, and to achieve certification was so high that Federal Express chose not to continue.

A significant subset of the Synthetic Vision concept has already been certified for commercial use. Today, Alaska Airlines is flying manual Category 3a approaches to Type 2 and 3 airports with a 50 foot decision height and 700 RVR (Runway Visual Range), via a combination of an inertially based Flight Dynamics Inc. head-up guidance system (HGS), and ILS equipment. The system does not include a weather penetrating sensor, but does allow the pilot to maintain an outside scan, and greatly enhances the precision of manually flown approaches.

While these previous efforts to develop and flight test millimeter-wave sensors strongly suggest that a low-visibility imaging landing system is feasible, insufficient engineering data needed to predict system performance and support the design of an operational installation was produced.

1.2. OBJECTIVE

The objective of the Synthetic Vision Technology Demonstration program was to develop, demonstrate, and document the performance of a low-visibility, visual-imaging aircraft landing system. The experimental Synthetic Vision System components included on-board imaging sensor systems using millimeter-wave and infrared technology to penetrate fog, and both head-up (HUD) and head-down (HDD).displays. The displays presented the processed raster image of the forward scene, combined with suitable avionics-based stroke symbology for the pilot's use during a manually flown approach and landing. The experimental system, sometimes referred to as a functional prototype system, included all the functions (in prototype form only) required to accomplish precision, non-precision, and noninstrument approaches and landings in low visibility weather conditions.

An important part of this program was to identify and document issues concerning operational procedures, safety, performance requirements, and airspace system compatibility. To satisfy the objective, it was necessary to provide test data, flight demonstration, and study of certification issues such that aircraft operators, manufacturers, and government regulators could objectively see the capabilities of current technologies to understand its costs, benefits and risks.

1.3 TECHNICAL APPROACH

A preliminary technology survey was performed with the assistance of experts in the technologies of imaging sensors, image processing and cockpit displays. The survey confirmed the notion that the Synthetic Vision system concept is feasible. The survey also highlighted the numerous challenging technology and systems issues to be resolved. It was clear that insufficient engineering data existed as a basis for accurate performance predictions and for establishing system performance requirements. It was also clear that suitable imaging sensors did not exist in a form suitable for this flight demonstration, even though the state of the art of sensor technology appeared sufficiently advanced. Therefore, before a technology demonstration could be performed, one or more such sensors had to be developed.

While the predicted capability of infrared sensors to image airport scenes in fog and precipitation conditions was not promising, actual performance data for this scenario was not available, and infrared sensor technology could not be discounted. Since the use and development of infrared systems for imaging has been through several generations, it was decided that the project would need only to seek a suitable infrared sensor, rather than develop a new one. The limited resources available for sensor development were to be applied to the development of suitable MMW sensors.

In early 1988, a proof-of-concept demonstration was arranged by the Air Force Wright Laboratory for FAA and other government officials. It was conducted on the Lockheed C-130 landing system. The experimental Synthetic Vision System components included on-board imaging sensor systems using millimeter-wave and infrared technology to penetrate fog, and both head-up (HUD) and head-down (HDD).displays. The displays presented the processed raster image of the forward scene, combined with suitable avionics-based stroke symbology for the pilot's use during a manually flown approach and landing. The experimental system, sometimes referred to as a functional prototype system, included all the functions (in prototype form only) required to accomplish precision, non-precision, and noninstrument approaches and landings in low visibility weather conditions.

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In early 1988, a proof-of-concept demonstration was arranged by the Air Force Wright Laboratory for FAA and other government officials. It was conducted on the Lockheed C-130 organized as a voluntary community activity with extensive participation by all parts of the aviation community including the FAA certification organizations.

1.4 SCOPE

The diversity in technologies which comprise the Synthetic Vision concept (millimeter-wave sensors, IR sensors, head-up displays, human factors, image processing and systems integration) required the scope to be carefully constrained so as to be able to conduct a meaningful technology demonstration within the program's finite time and financial resources. The experimental system was limited, therefore, to the incorporation in a fixed wing aircraft of existing display technology, millimeter-wave and infrared sensors; and sufficient instrumentation to permit documentation of the weather, sensor system performance, and pilot performance. The scope was further limited to a set of experiments and demonstrations that could be set up and accomplished in approximately one year. Millimeter-wave sensors were developed only to the extent possible in one year. Information fusion was pursued only to the extent necessary to achieve the simultaneous display of stroke symbology with raster imagery on the HUD. Existing techniques for image enhancement were applied only as necessary to sharpen the image of the runway complex.

A related application of weather penetrating sensor technology, the detection of vessels whose masts penetrate the obstruction clearance plane of the ILS approach to Boston's Logan International Airport, was undertaken for the FAA New England Region (the New England Region provided the additional funding required). The Program Office evaluated the capability of the MMW sensor technology for this use, developed system requirements and estimated acquisition costs for the Regional Office.

2. PROGRAM MANAGEMENT OVERVIEW

2.1. MANAGEMENT APPROACH

The Technology Survey revealed engineering challenges requiring a diverse contribution of expertise, facilities and financial resources that only a joint team of government agencies and industry could provide. This team was led by the Federal Aviation Administration and assembled over the course of the program. A diagram of the project management team is found in Figure 1.

2.1.1. Federal Aviation Administration

The FAA initiated this project at the direction of the Administrator, Mr. T. Allan McArtor. It was managed within the FAA Research and Development Service under the Associate Administrator for Development and System Engineering. Inter-agency agreements with the Air Force, National Oceanic And Atmospheric Administration (NOAA), and National Aeronautics and Space Administration (NASA) were used extensively for this project. The FAA transferred the majority of the project funds to the Air Force, but also transferred funds to NOAA for a grant to the Maryland Advanced Development Laboratory and to NASA for administrative and technical support and official travel.

2.1.2. Specialized Technical Experts

Throughout the course of the project, the advice of specialized technical experts was sought to understand technical system requirements, to provide independent assessments during the progress of sensor developments, and to maintain the validity of the experiments and data analyses.

Dr. Robert D. Hayes of RDH Incorporated, an expert in millimeter wave sensor performance, assessed the available technology in weather penetrating sensors, contributed to the development of prototype sensor requirements, advised the management team during design reviews, developed theoretical predictions of sensor performance in weather, and advised the data analysis teams. Dr. Hayes also defined the system requirements for the proposed Harbor Vessel Detection System at Boston's Logan International Airport.

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Mr. Paul Mengers of PAULTEK Incorporated, designer and inventor of electro-optical and image-processing systems, assessed the state of the art of real time image enhancement test program, and designed and built an optical system for through-the-HUD inflight video recordings.

Dr. J. Allen Zak of Hughes/STX, a meteorologist, provided essential expertise regarding atmospheric conditions encountered during aircraft operations and the sources and types of instrumentation required to measure those conditions. He participated in the development of the Synthetic Vision tower test plan and the plans for atmospheric data collection at the tower and in the aircraft, and performed reduction and quality control of the data collected during the flight tests. Dr. Zak coordinated the real time nationwide weather forecasting that led to successful encounters with the special cases of low visibility, rain and snow conditions. Dr. Zak served throughout the program as a member of the Program Office, participating in program planning, schedule and resource tracking, coordinating the support activities of the technical experts, and progress reporting. He was responsible for the coordination of the Harbor Vessel Detection Requirements Study.

2.1.3. U.S. Air Force

The United States Air Force Wright Laboratory, Flight Dynamics Directorate, Wright-Patterson APB, OH, was the lead Air Force organization. In 1988 the Autonomous Landing Guidance (ALG) Project, managed by the Flight Controls Division, was investigating concepts using infrared and millimeter-wave imaging sensors to produce images on head-up displays in conjunction with other symbology on the HUD; concepts which were common to the Synthetic Vision System concept. The FAA and Air Force agreed to collaborate in a joint Synthetic Vision Technology Demonstration Project to capitalize on the existing efforts and research capabilities at Wright Laboratory. The Wright Laboratory also assigned personnel to full time positions as the Deputy Program Manager, resident in the Synthetic Vision Program Office, and as the Tower Test Director, resident at Wright Patterson AFB.

Wright Laboratory possessed technical expertise, engineering research and test facilities, and contracting capabilities that were particularly well suited for this project. Of early benefit to the project was the Lockheed C-130 High Technology Test Bed, made available by the Air Force via the ALG program, for a proof-of-concept demonstration. The Air Force Materiel Command at Wright Patterson AFB also made available the Program Research and Development Announcement (PRDA) contracting method that can shorten competitive procurement time and test program, and designed and built an optical system for through-the-HUD inflight video recordings.

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2.1.6. Participating Industry Organizations

This technology demonstration project was dependent on the knowledge, experience, resources, and engineering capabilities of private industry. Numerous firms voluntarily contributed time, engineering talent, and equipment to this effort for little or no compensation. Major government contracts were also required to prepare for and complete the demonstration. The scope of these contracts and the participating industry organizations are identified below.

In April 1989, an Air Force Program Research and Development Announcement (PRDA) was published by Wright Laboratory in the Commerce Business Daily inviting bids to design, develop, tower test and flight test an imaging weather penetrating sensor. Ten proposals were submitted, and TRW, Lear Astronics, Martin Marietta, and Eastman Kodak were awarded Phase 1 contracts to provide sensor designs. After the sensor design presentations, the project selected Lear Astronics to build and test their 94 GHz Frequency Modulated Continuous Wave (FMCW) radar. Meanwhile, Wright Laboratory, on behalf on an Air Force project, awarded contracts to Kodak and TRW for development of their designs.

The design of a 94 GHz radar, by **Lear Astronics Corporation** of Santa Monica, CA, was quite innovative, offering the potential of impressive performance with moderate development risk. Designed specifically for the Synthetic Vision Technology Demonstration, it was selected as the primary and most promising candidate for experimental prototype integration and flight test. However, successful and timely completion of the tower tests and suitability flight tests was a prerequisite to full scale flight testing.

The risk of depending on a single sensor development for the flight demonstration and the need for characterization of 35 GHz sensor performance led to a contract with **Honeywell Systems Research Center** of Bloomington, MN, for design and fabrication of a sensor at that frequency. Honeywell had previously manufactured 35 GHz radars for another Air Force application that, with the addition of a suitable antenna and an upgraded signal processor, could be used for tower testing and perhaps flight testing. On behalf of the project, the Air Force Sacramento Air Logistics Center, Microelectronics Technology Support Program, awarded the contract to Honeywell in June 1991. It was modified in December 1991 to upgrade the radar to a flight worthy configuration and to provide flight test support when it became clear it would be needed as the primary test sensor.

Wright Laboratory offered modest contracts to other sensor manufacturers to bring existing sensors to the tower for Synthetic Vision performance testing. One such contract was awarded in October 1991 to **UTC/Norden Systems** of Norwalk, CT, to test their **95 GHz** TALONS radar system. The tests were conducted successfully from October 1991 through February 1992. The Program also tested in the tower facility the **3-5** micron **FLIR camera** designed in the design competition phase and built for the Air Force by **Eastman Kodak** of Rochester, NY. Kodak also provided and supported another version of the same design in the flight test phase of the Program through an arrangement with TRW.

Georgia Technology Research Institute (GTRI) of Marietta, GA, was awarded contracts by Wright Laboratory and TRW to independently analyze sensor performance data in the Tower Test and Flight Test phases of the Program. Under the first contract, awarded by Wright Laboratory in April 1991 for the tower tests, GTRI wrote portions of the test plan, developed data collection and reduction software, calibrated each sensor, and completed the sensor performance analysis. TRW also awarded a subcontract to GTRI in August 1991 for support of the flight test task.

The Air Force Microelectronic Technology Support Program issued a delivery order to **TRW Military Electronics and Avionics Division (MEAD),** of San Diego, CA, to serve as the prime contractor for the System Integration, Evaluation and Demonstration (SEID) task of the Technology Demonstration. The division of responsibilities between TRW and the participating organizations is illustrated in Figure 2.

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An important element of the cooperative management approach for the System Integration, Evaluation and Demonstration (SIED) task, agreed to between TRW, the MTSP contracting office, and the Synthetic Vision Program Office, was the level of attention given to the Program Plan and within it, the Resource Allocation Plan. The Program Plan was developed as an expansion of the contract Task Assignment Plan as a joint effort on the part of all the participants. The Resource Allocation Plan consisted of the planned monthly spending for each major line item in the Work Breakdown Structure, found in the Program Plan, over the life of the contract. The Program Office, the TRW managers, and the subcontract managers monitored actual spending with respect to the plan, anticipated problems, and were able to make informed and timely adjustments. While it was consistent with the contractor's monthly financial reporting system required by the government, the Resource Allocation Plan provided more detail and provided the information in a more timely fashion.

2.2. SCHEDULE

The schedule for the Synthetic Vision Technology Demonstration project is presented in Figure 3. Each of the schedule elements shown is briefly discussed below; an overview of each of the major program elements is provided in section 3 of this Executive Summary.

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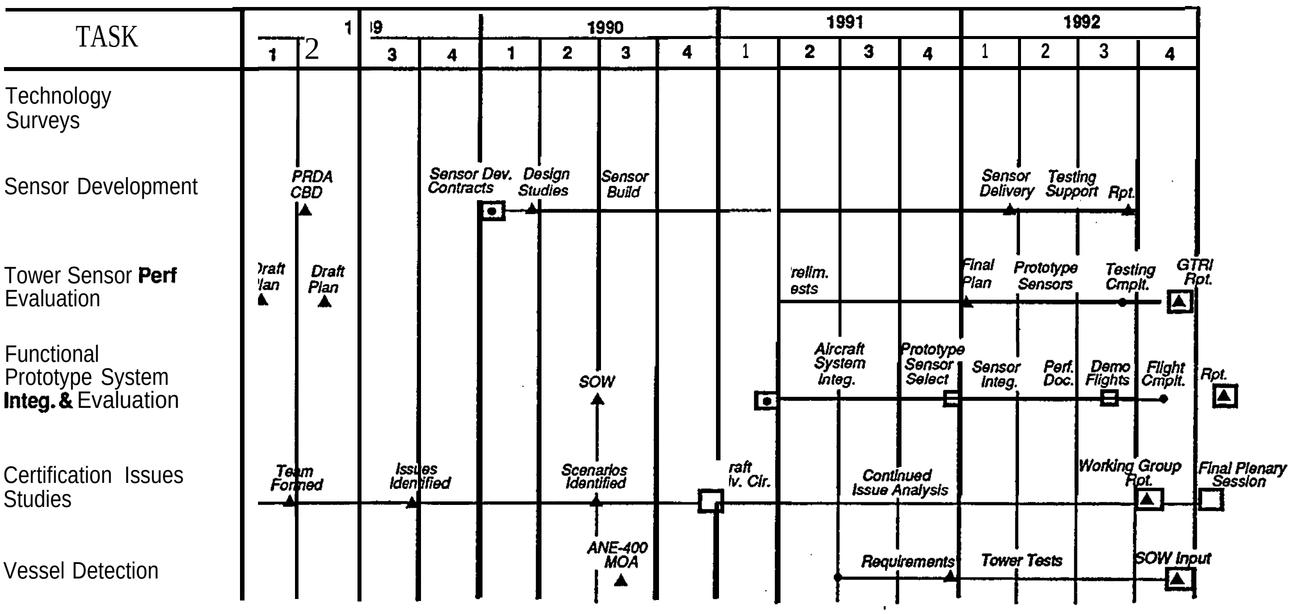

Figure 3. Synthetic Vision Technology Demonstration Program Schedule

Preliminary sensor tower tests at the Air Force Target Characterization Facility commenced in May 1991. An Air Force owned 35 GHz sensor was first tested in May 1991 to validate the test plan procedures, data acquisition and reduction systems. Tests of the initial Lear Astronics 94 GHz sensor were performed in August 1991. A 95 GHz Norden Systems radar was successfully tested from November 1991 through February 1992. An Air Force Kodak 3-5 micron imaging infrared system was tested from March through May 1992. The flight configuration of the Honeywell 35 GHz sensor system was tested from April to May 1992, found conditionally satisfactory for flight, and then installed on the flight test aircraft in June 1992. Reports of all tower test results were provided in January 1993 by the tower test contractor, Georgia Technology Research Institute.

A contract was awarded in June 1991 to Honeywell, Inc. to build a new antenna and provide an integrated 35 GHz radar system for tower and limited flight testing by October 1991. After it was learned that Lear Astronics could not deliver a suitable system in time for tower and flight testing, the Honeywell contract was modified in December 1991, to provide a fully flightworthy system by February 1992. The Honeywell system was delivered and submitted to hot bench testing in February, returned to Honeywell for modifications in March, and sent to the Air Force for Tower Testing at the end of March. Shakedown flight testing began in mid May.

2.2.4. Experimental System Integration, Evaluation and Demonstration

A contract was awarded in March 1991 to TRW as the prime contractor for design and integration of the experimental flight demonstration system and conduct of flight test activity. Modifications to the Gulfstream II test aircraft were completed in December 1991, hot bench testing in February 1992, and final integration of the experimental system in May 1992. Shakedown flights were conducted in May and June. Full scale flight tests began in July 1992 with the 35 GHz sensor system, a GEC head-up display and a Kodak 3-5 micron infrared camera. In October, the 35 GHz system was temporarily removed and the Lear Astronics 94 GHz sensor installed and flight tested. The 35 GHz system returned in November and flight tests continued until mid December. The final report on this activity was provided in February 1993.

2.2.5. Certification Issues Study Team

The Certification Issues Study Team was organized in 1989, holding its first meeting in March, and the last of eight plenary sessions in January 1993. The draft advisory circular and certification roadmap were completed by the team and presented at the sixth meeting in March 1991.

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3. TECHNOLOGY DEMONSTRATION PROGRAM ELEMENTS

3.1. TECHNOLOGY SURVEY

A technical advisory team, assembled for the project under a grant to the Maryland Advanced Development Laboratory (MADL) conducted a survey of current Synthetic Vision technology areas and published the Preliminary Technology Assessment Report in January 1989. The objectives of the survey were to verify the feasibility of a demonstration with current technology, identify important technical issues and estimate system performance requirements. The requirements listed below are not the final findings of this project, which are described later in this volume in Section 3.4.7 (Sensor Performance), Section 3.4.8 (Image Quality), Section 3.4.9 (Pilot/System Performance) and Section 3.4.5 (Lessons Learned). A result of a sixty day study, they were meant to be used for program planning; that is, to determine what must be done to achieve a flight demonstration, to develop a realistic schedule, to estimate costs and to establish resource priorities.

3.1.1. Estimated Demonstration System Requirements

System requirements for the experimental demonstration system were founded on the assumption that a head up display (HUD) would present sensor derived imagery of the airport scene and essential avionics information that would enable the pilot to manually perform the approach, flare, landing, rollout and taxi, in spite of low visibility conditions. Imagery and position related avionics information would be projected conformally in position and scale, such that in visual conditions, image features, such as the runway, on the HUD would perfectly correspond with the real world. The system would ideally be independent of ground based navigation aids and would have sufficient reliability to meet experimental aircraft certification requirements.

- System Requirements. The team proposed the following functional system requirements:
  - Minimum range for runway acquisition: 7000 feet from the threshold.
  - Accurate horizontal and vertical image registration.
  - Image processing in real-time , (i.e. negligible display latency).
  - Obstacle detection sufficient to confirm a clear runway.
  - Enable touchdown accuracy laterally within 27 feet of centerline, and longitudinally within 700 feet of the touchdown zone.
  - Provide flare cues to enable touchdown accuracy.
  - For fail operational system components, probability of failure 10^{-9}

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3.1.2 Technical and Systems Issues To Be Resolved.

The team found several issues needing resolution. They are summarized below:

Sensors.
- Is the optimum technology active radar or passive radiometer?
- Is 35 GHz or 94 GHz the best frequency?
- Is infrared (FLIR) useful for some operations? If so, at 3 to 5 microns or 8 to 12?

Image Processing.
- How much and what kinds are required?
- Can required image processing be performed at the required image update rate?

Registration.
- Can the accuracy of image and HUD registration be achieved and maintained?

HUD Symbology.
- What information must be displayed and is it compatible with the display of the imagery?

Weather Models.
- Are current models sufficient to predict sensor performance in all weather conditions?

Reliability.
- Can the required levels be realized?

3.2 SENSOR DEVELOPMENT

The objective of the sensor development effort was to obtain at least one imaging, weather penetrating sensor to enable flight demonstration of the Synthetic Vision concept in zero-zero conditions. Sensor development was necessary because an existing sensor, satisfactory for flight demonstration of the Synthetic Vision concept, had not been found. Nevertheless, sensor technology did seem to be sufficiently advanced; so the need was to redesign current technology into a suitable package for the flight demonstration. It was estimated that the sensor development would take a manufacturer twelve months, at an estimated cost of $2 million, including the follow on test support.

3.2.1. Demonstration Sensor System Guidelines for Bidders

The guidelines provided to potential bidders for development of the demonstration sensor system stated that to support low visibility landing operations, the sensor must produce an image of the runway and adjacent complex at long enough ranges to permit a safe descent. The image of the runway must have sufficient contrast and resolution to enable the pilot to detect it, identify it and track its location. The sensor system with the integrated aircraft avionics and headup display (HUD) must accurately register the image with the outside view and correct for aircraft roll, pitch and yaw maneuvers. Finally the sensor must produce the image with a variety of surface materials and conditions, and through a variety of atmospheric obscurants (fog, rain, snow). Precise specifications were difficult to define so the following guidelines were provided to the bidders:

- Range (kilometers):	Enable Runway Detection	5
	Enable Runway Identification	3
	Confirm Obstacle Clear Runway	2

- Assume three degree glide slope.
- System must be entirely self-contained; no ground aids required to land.
- Capable of supporting flight evaluations/demonstrations in fog, rain and snow.
- Form, fit and function capable of integration on executive class jet aircraft; like Gulfstream
- Produce image in real-time and in real world perspective for display head up.

The project expected to learn more about systems requirements from the first phase of the development contracts in which design studies and technology tradeoff analyses would be performed.

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The project expected to learn more about systems requirements from the first phase of the development contracts in which design studies and technology tradeoff analyses would be performed.

Following evaluation of the design studies, the Synthetic Vision project chose one, the Lear Astronics design, for Phase 2 Fabrication. The Kodak FLIR offered impressive performance, but according to the manufacturer's analysis could not promise sufficient range in fog and rain to serve as the primary sensor. The TRW 94 GHz radiometer was a very interesting system, but a configuration with sufficient field-of-view could not be fabricated in time for the flight activity.

The Flight Dynamics Directorate, in association with the Avionics Directorate, the Navy, Rome Air Development Center, and others, proceeded with fabrication of the Kodak FLIR and a modified configuration of the TRW radiometer. Both are passive sensor designs.

3.2.3. 94 GHz Radar Fabrication.

The Phase 2 fixed price contract was awarded to Lear Astronics in late June 1990 and required delivery of a working system by the end of April 1991. The fabrication schedule was extremely aggressive, however the sensor was not ready by April 1991. By the end of May, believing the radar lacked sufficient performance, the contractor attempted to enhance it with new components to increase power and reduce system losses. As a result of these difficulties, the government sought to arrange an acceptance test, in August 1991, prior to a Phase 3 commitment. In January 1992, after several attempts to reach an agreement, the government accepted delivery of the system and terminated the contract without proceeding to Phase 3. Later, Lear Astronics made new arrangements to conduct an acceptance test and proceed to the test aircraft, under a subcontract to the prime contractor for flight integration and testing, TRW. The sensor in the configuration in which it was tested in the tower is shown in Figure 4.

3.2.4. 35 GHz Sensor Procurement and Fabrication

Because only one sensor, the Lear Astronics 94 GHz radar, was chosen for the competitive development, the project lacked the means to test and characterize 35 GHz performance. A search for 35 GHz sensors yielded a relatively low cost solution; an existing radar built for another Air Force application. To be assembled with components from the manufacturer, Honeywell, Inc., and the Air Force, this system would be tested at the tower to obtain the desired 35 GHz

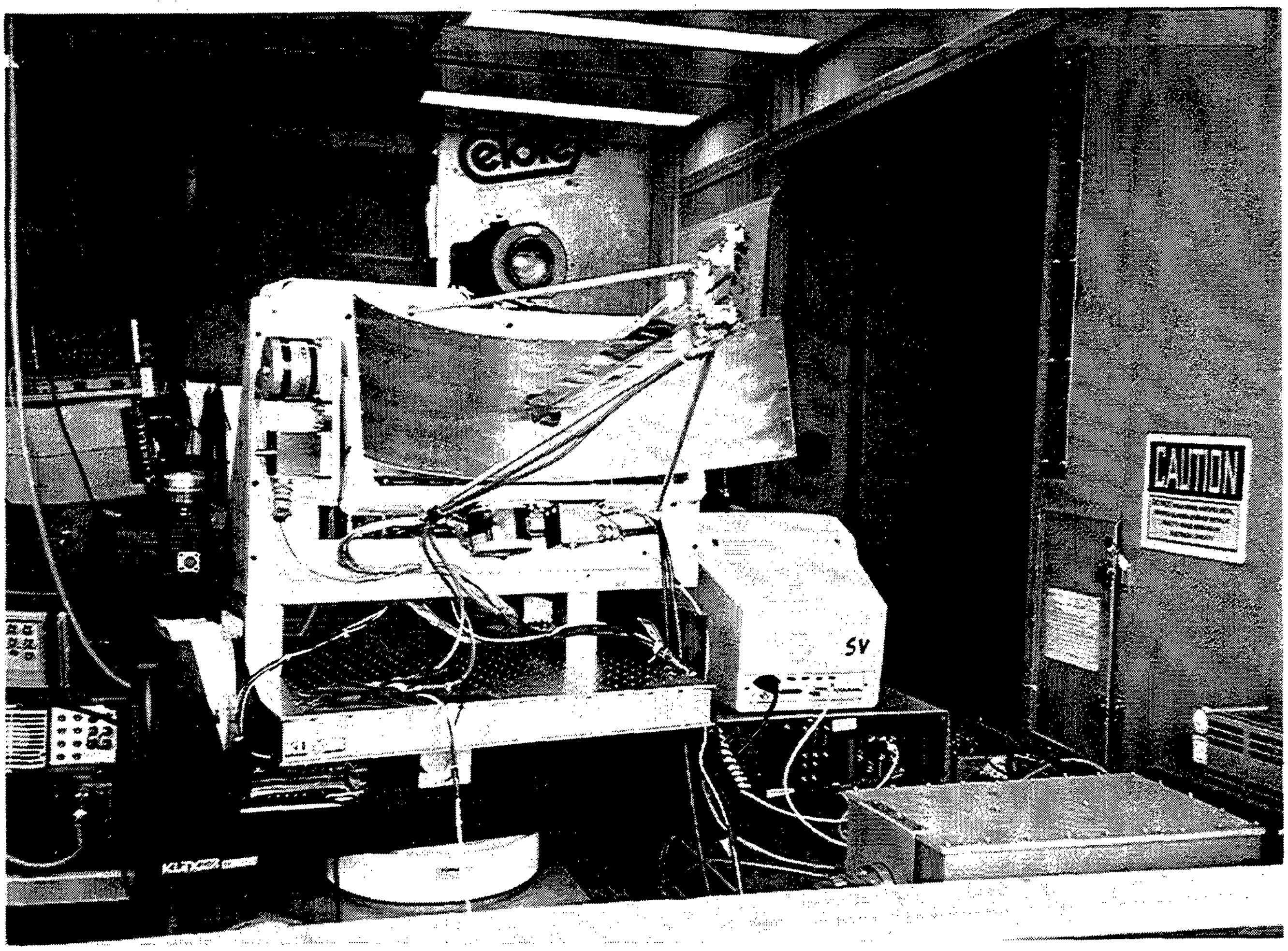

Figure 4. Lear Astronics 94 GHz SVS Imaging Radar

performance and phenomenology data. The project funded fabrication of a new electromechanical scanning antenna, built by Malibu Research Associates, that was designed in a form and fit suitable for potential flight tests. As a result of this activity, the program would not only obtain 35 GHz data, but also a backup sensor for the flight tests, in case the higher risk 94 GHz radar development was not successful.

In June 1991, Honeywell. was awarded a delivery order by the Microelectronics Technology Support Program at the Air Force Sacramento Air Logistics Center, to provide an integrated sensor system for tower testing. The delivery order was modified in December 1991, after it became clear that the primary flight test sensor would not be ready in time. The modification entailed sensor system upgrades for flightworthiness, engineering support for aircraft integration, and flight test support. The 35 GHz sensor was delivered in February 1992, hot bench integration testing was successfully completed, and the sensor was sent to the Air Force tower in March. The components of the sensor are shown in Figure 5.

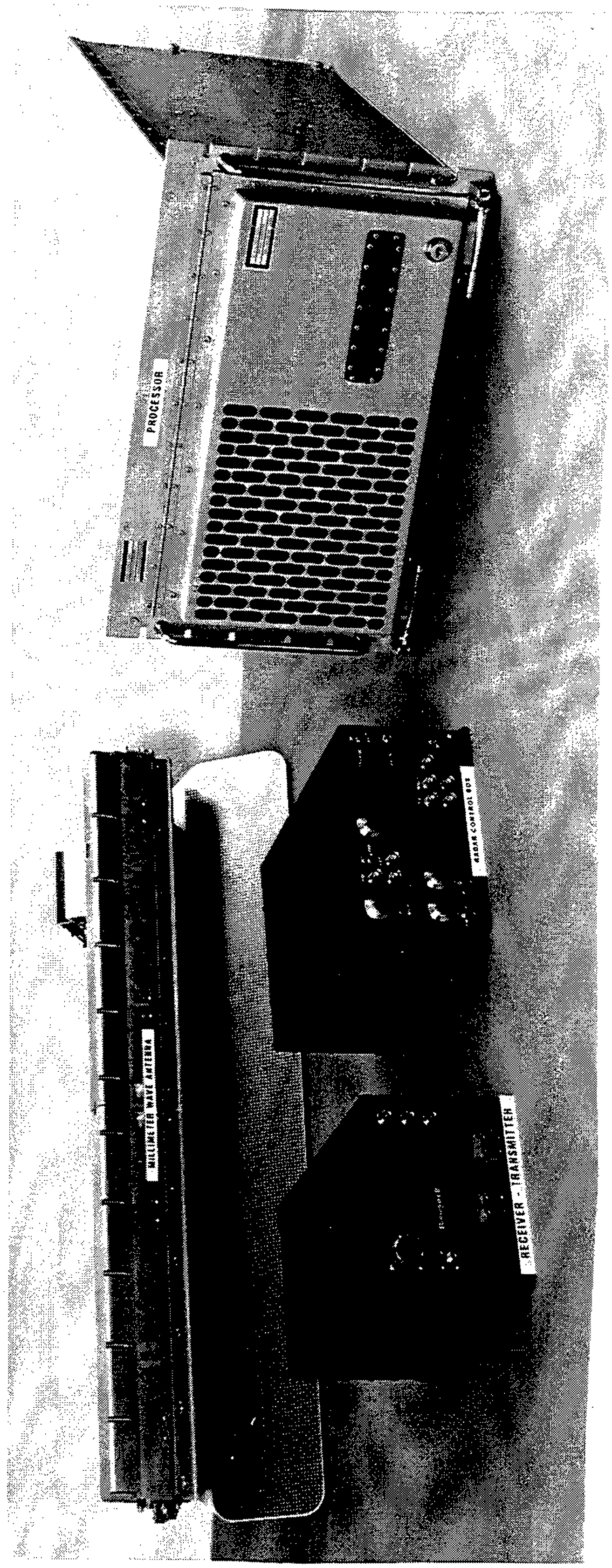

Figure 5. Honeywell 35 GHz SVS Imaging Radar Components

3.3. SENSOR TOWER TESTING.

Sensors that can produce images of the airport scene through fog and precipitation represent the key enabling technology for Synthetic Vision. Primary objectives of the tower tests were to calibrate each sensor, develop a performance data base, determine performance in clear weather, determine performance in low visibility fog, rain and snow conditions, and establish suitability for flight testing. An additional objective was to learn as much as possible about the characteristics of the low visibility weather conditions that affected sensor performance.

The Wright Laboratory Avionics Directorate owns and operates the Target System Characterization Facility, otherwise called the tower facility at Wright Patterson AFB, which overlooks a heavily instrumented, non-operational runway complex at a look-down angle of 3.5 degrees as shown in Figure 6. A top view drawing of the area with some of the key landmarks is provided in Figure 7. It is an ideal site for sensor testing in a controlled environment. The elevated sensor test position at the tower was equipped by the SVS Program with a precision data acquisition system consisting of an automated motion table, computer with high capacity hard drives and digital frame grabber, high resolution camcorder, video recorders, video monitors, and blackbody calibration sources. GTRI designed the data acquisition system and wrote software that automated data collection and also allowed "quick looks" at the data through imagery and signal levels to monitor test progress and data quality. The runway scene was equipped with calibrated reflectors for millimeter wave measurements and an extensive meteorological measurement suite. This suite enabled the collection of temperature, radiance, humidity, rain rate, drop size, and visual range data at high sample rates. The Wright-Patterson AFB weather station provided tailored forecasts and observations in support of the tests.

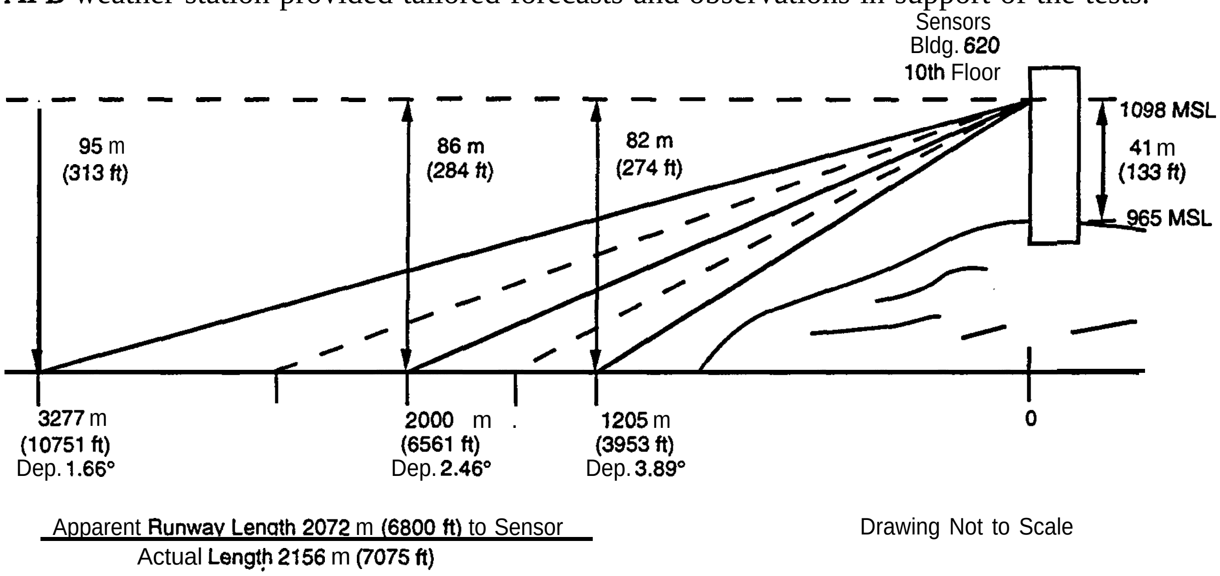

Figure 6. Elevation drawing of test area.

The scene dimensions, feature locations, and surface materials were surveyed to provide precise ground truth for comparison with sensor performance.

The Air Force Wright Laboratory Control Systems Development and Applications Branch assumed responsibility for the planning and conduct of the tower tests and assigned a Tower Test Director. The Tower Test Director served as the technical point of contact for the procurements of test equipment, meteorological instrumentation and data reduction, separate contracts with sensor providers, and the contract for the Tower Test Support with GTRI. The Tower Test Director managed the development and publication of the Tower Test Plan which served not only the Synthetic Vision project, but also other sensor test tasks at the same facility. The Synthetic Vision Program Office defined test objectives. GTRI, and the technical consultants wrote major technical sections such as the requirements for data elements, instrumentation, analysis methodology, data management, and test procedures for the various types of sensors. The plan was completed and approved in May 1991. GTRI had primary responsibility for the actual data management, reduction, and analysis. Preliminary sensor tests were conducted during that summer to validate and refine the test plan. It was revised in August 199 1 to add the detailed "Radar Method of Test" and in February 1992 to add the detailed "IR Method of Test" (not a full scale tower test) was conducted in August 1992. The Tower Test Schedule is shown in Figure 8.

The Tower Test Plan required that baseline tests of each sensor be conducted to calibrate the system parameters and provide the ideal clear air performance control data set for comparison with sensor performance in fog, rain and snow. The planned test matrix called for a minimum of twelve complete data runs of four different weather categories with three runs each. The four categories were clear air, fog, rain and snow. The maximum prevailing visibility for the latter three categories was 1 1/2 miles. For the infrared sensors, 24 hour duration diurnal baseline tests were conducted because of the performance dependencies on sun angle, thermal history, and time of day.

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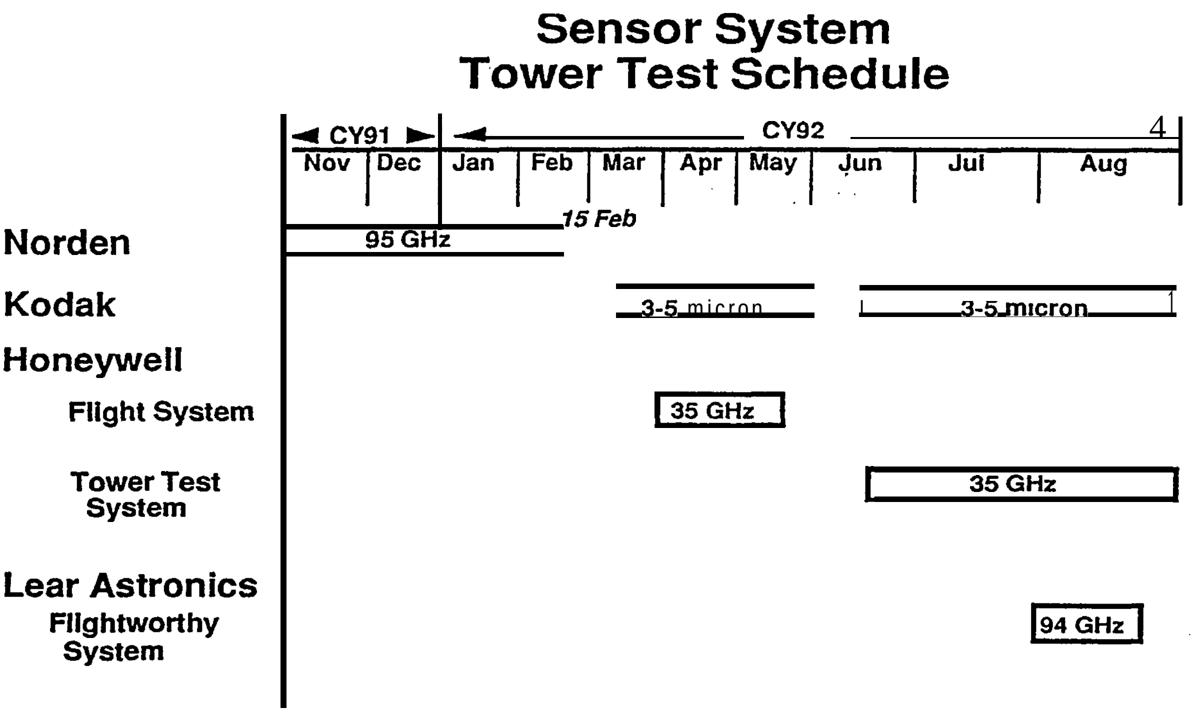

Figure 8. Synthetic Vision Sensor Tower Test Schedule

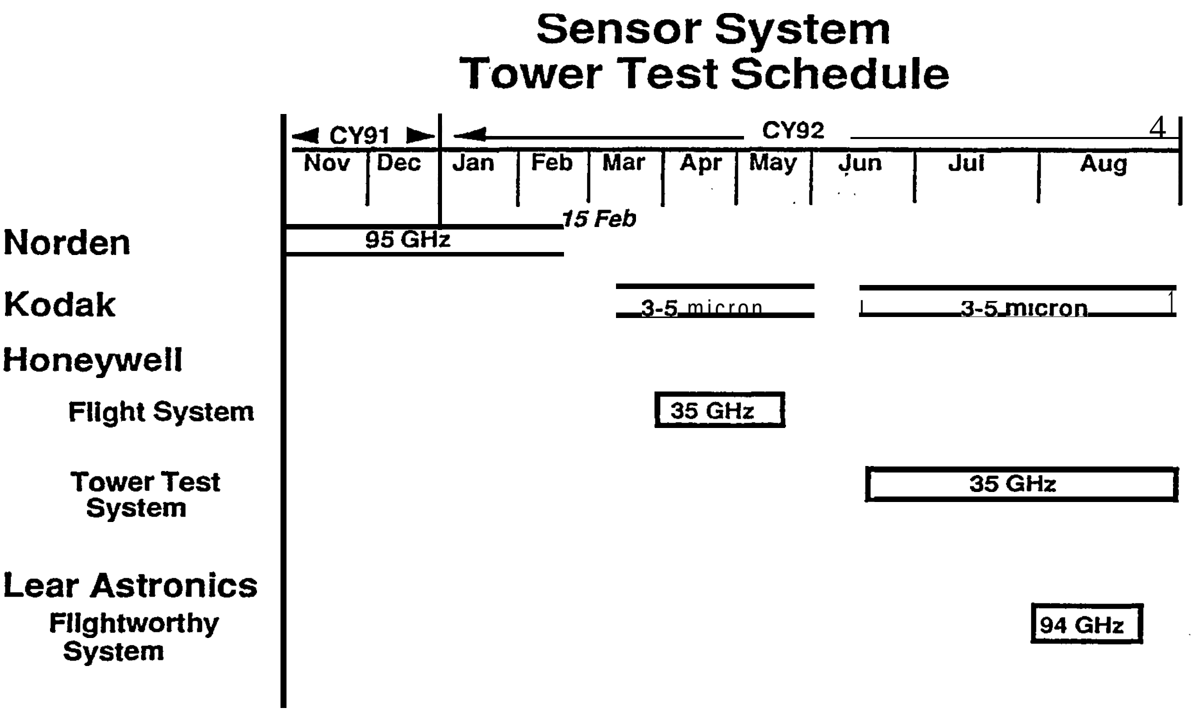

Figure 8. Synthetic Vision Sensor Tower Test Schedule

The complete operating specifications for each test sensor were determined at least once during the testing period. Some characterization activities required partial disassembly of the test sensor and the use of special purpose test equipment, so more frequent measurement of these parameters was not practical. Some of the specifications had to be ascertained from previous off-site measurements or from manufacturer's test data. The six mmw radar sensors tested at the tower and their pertinent specifications are listed in Table 1.

Table 1. MMw Radar Sensors Tested At Tower

Sensor Code	Manufacturer	Frequency	Waveform	Antenna /Polarization	Signal Processor	Remarks
LA1	Lear Astronics	94 GHz	FMCW	parabolic* /circular	DSP	develop-mental
LA2	Lear Astronics	94 GHz	FMCW	parabolic** /vertical	DSP & EVS	SVTD candidate
NS1	Norden Systems	95 GHz	pulsed	parabolic /circular	none	non-candidate
HI1	U.S. Air Force	35 GHz	pulsed	slotted W/G /horizontal	none	non-candidate
HI2	Honeywell Inc.	35 GHz	pulsed	slotted W/G /circular †	DSP	SVTD candidate
HI3	Honeywell Inc.	35 GHz	pulsed	slotted W/G /horizontal	none	non-candidate

* Front-fed dual parabolic reflector with gear drive
** Cassegrain fed dual parabolic reflector with resonant scan
† Slotted waveguide fed reflector with electromechanical "Eagle scan"
Abbreviations: W/G = waveguide, DSP = digital signal processor, EVS = video processor

A sensor configuration code based on the manufacturer's name and a configuration sequence number was established to label the data from each sensor tested. Two configurations of the Lear Astronics 94 GHz radar sensor, an Air Force 35 GHz radar sensor, and two configurations of Honeywell 35 GHz radar sensors were tested; the configurations differed in antenna selection, transmitter, and signal processor. The Norden Systems TALONS 95 GHz radar, although not considered a candidate Synthetic Vision sensor, provided the most extensive set of MMW radar adverse weather performance data collected on this project. Only the LA2 and HI2 radars were SVTD candidate MMW radar sensors and continued on to flight testing.

3.3.1.2. Infrared Sensors

An infrared (IR) sensor is able to image a runway scene based on the differences in temperature, emissivity, and reflectivity of the pavement areas and the bordering grass-covered areas, as shown in Figure 10. An IR camera receives thermal radiance from the scene surfaces, and a lens focuses that energy on a sensitive detector element or array of elements. The wavelength range accepted by an IR camera is based on the type of sensitive detector element used. Image contrast is developed by the differences in radiance received from the typically warmer pavement and the typically cooler grass areas within an airport scene. The actual radiance difference is a function of environmental heating and cooling during the daily cycle, grass moisture, and meteorological events.

The IR sensor systems used in the SVTD program to collect data in the 3 to 5 micron infrared band were focal plane array cameras with Stirling-cycle refrigeration for sensor cooling. Most of the infrared image data were collected with the Kodak Model KIR-310 infrared camera system, shown in Figure 11 as it was installed in the tower test facility. Image data were also acquired with a Mitsubishi Electric Corporation model IR-5120C infixed camera. Both of these instruments utilized platinum-silicide (PtSi) focal plane array sensors and provided the image data in an RS-170 video signal format. Important characteristics of the two camera systems are listed in Table 2.

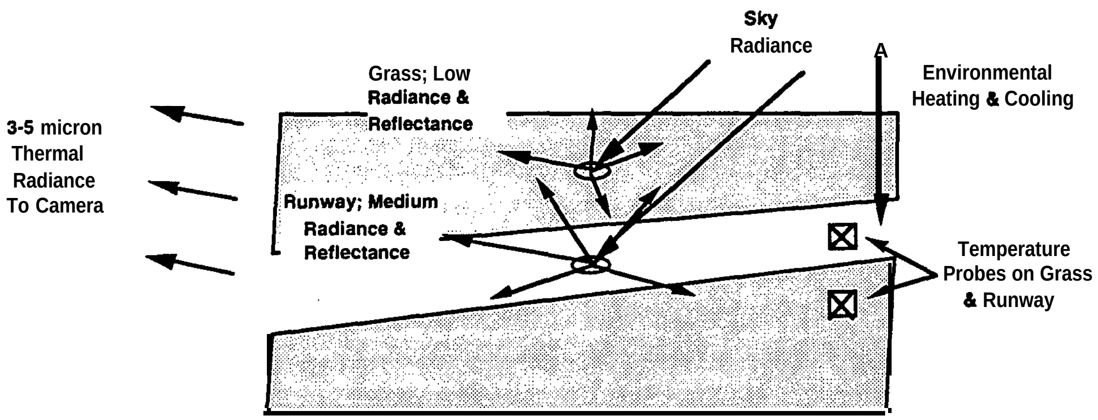

Figure 10. IR detection of a runway.

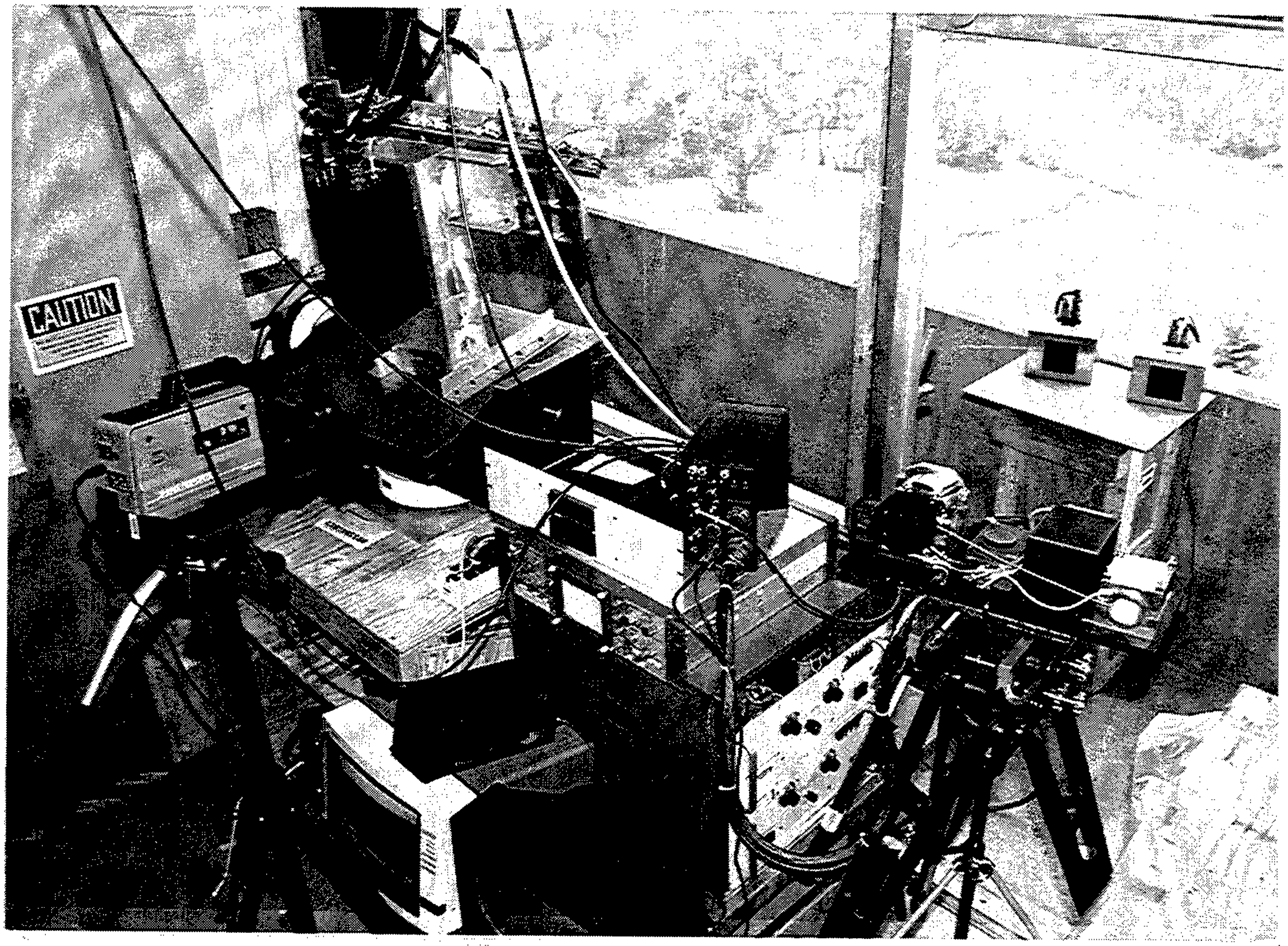

Figure 11. Kodak 3-5 micron Sensor System Used In Tower Tests

Table 2. Characteristics Of Camera Systems

Characteristic	Kodak KIR-310	Mitsubishi IR-5120C
Detector	PtSi FPA	PtSi FPA
Number of array elements	640X486	512X512
Response band	3.2-4.1 microns	3-5 microns
Lens focal length	27.5 mm	50 mm
Lens aperture	f/1.7	f/1.2
Field of view	32°X25°	14°X11°
NEDT (Noise Equivalent Difference Temperature)	0.17° c	0.15° c
Cooling method	Stirling cooler	Stirling cooler
Analog output	RS-170 video	RS-170 video

2.3.2. Sensor Performance Measures

Sensor performance features are a measure of a sensor's effectiveness in imaging the airport scene and are specific to the individual sensor design. Phenomenology characterizes the test scene environment in fundamental engineering values that are related to the sensor wavelength but are independent of a particular sensor design. Resolution and contrast are examples of sensor performance features. Examples of phenomenology values are radar cross section for a target or clutter area, volumetric radar cross section for precipitation, and atmospheric attenuation. Radar phenomenology values are frequency sensitive.

2.3.2.1. Performance Features

Sensor data collected during tower tests were processed to extract the specific sensor performance features listed in Table 3. These performance features were selected to apply equally well to the MMW and IR imaging sensors tested at the tower. Prior to feature extraction, the "raw" sensor data were converted into standard units of measure appropriate to each sensor technology. MMW radar sensor data were calibrated to units of equivalent received power, and IR sensor data, to units of equivalent received radiance. The term "signal" in this context refers to the amplitude values of the calibrated sensor data. The specific formulas for calculating the performance features are presented in Sections 7.1 (MMW) and 7.2 (IR) of Volume 2 (Sensor Tower Testing) of this report.

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Table 4. MMW Phenomenology Features

Feature Name	Abbreviation	Description
Normalized RCS	σ^0	Radar cross section per unit area of surface.
Atmospheric attenuation	a	Reduction of apparent target RCS due to airborne material (liquid water).
Volumetric RCS	σ_v	RCS of the airborne water, norm,, z:d to volume.

A calibrated radar sensor can measure the RCS of a target or clutter area by substituting received power values into the radar range equation and solving for RCS. The resulting RCS is expressed in units of square meters or decibels relative to one square meter of RCS. This RCS measure is appropriate for characterizing a "point" target such as a vehicle or an area of clutter comprised of collection of objects, either natural or man-made. Radar clutter can be local: such as a single tree, or distributed over relatively homogeneous extended surface areas, such as pavement or grass.

Conditions in the intervening atmosphere between a MMW radar and a target can degrade the radar's ability to detect and image that target, as shown in Figure 12. Airborne moisture due to fog and precipitation (rain, sleet, or snow) causes scattering and diffusion of the radar's electromagnetic waves. Atmospheric effects are separated into attenuation and volumetric backscatter.

Attenuation is the loss of apparent target RCS due to the intervening atmosphere. Atmospheric attenuation applies over the entire radar propagation path, from the radar to the target and back to the radar, or twice the target slant range for a monostatic radar (i.e., one with the transmitter and receiver collocated). Attenuation reduces the range at which a radar can resolve runways from bordering grass areas, due to a reduction in apparent grass clutter RCS and runway clutter RCS.

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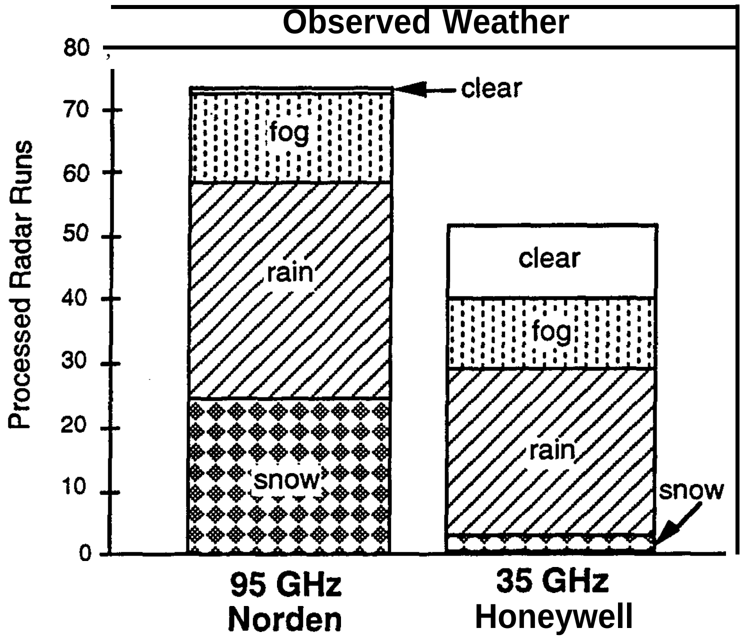

Figure 13a. MMW Test Data Matrix Sorted by Observed Weather.

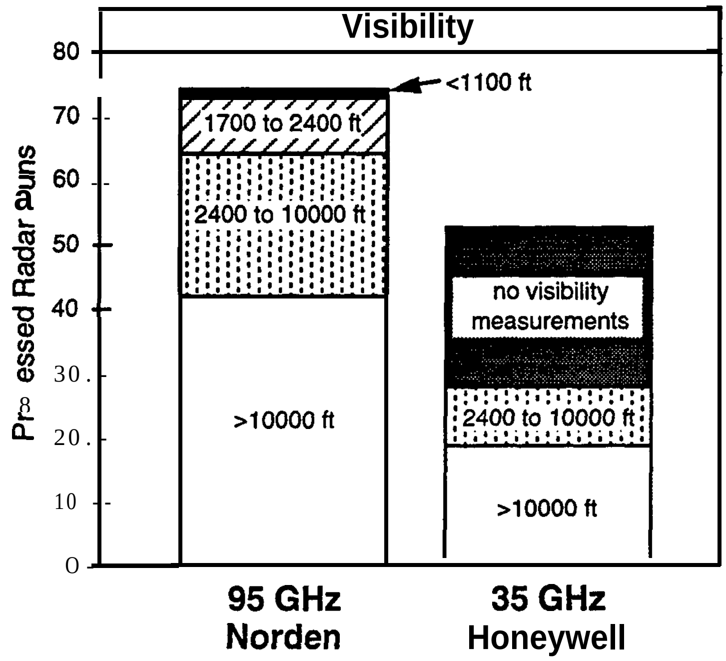

Figure 13b. MMW Test Data Matrix Sorted by Along-Path Visibility

Table 5. MMW Radar Sensor Data Matrix

MMW Sensor Description	Measurements Performed	Total Runs		Number of Runs Processed (by Meteorological Conditions)				
		Collected	Processed	Clear	Snow	Fog	Rain	F&R
Lear development system	sample runs	3	3	3	0	0	0	0
Lear flight system	acceptance test	6	3	3	0	0	0	0
Norden TALONS	full matrix	165	76	4	25	14	33	0
Honeywell development system	sample runs	11	6	6	0	0	0	0
Honeywell flight system	full matrix	46	35	5	3	3	20	4
Honeywell spare unit	sample runs	25	13	2	0	9	2	0

The very late delivery of the 94 GHz sensor to the tower facility precluded testing of the sensor in any conditions other than clear air.

3.3.4. MMW Sensors Baseline Performance

Analysis of the performance of the MMW sensors in clear weather established a performance baseline against which the effects of weather could be determined. Baseline measurements also allow comparisons of perceived image quality to the operating parameters of these particular radar sensors. Figure 14 shows how the radar resolution cell sizes at 2 km range compare with the width of the runway at the tower test scene. The radar resolution cell dimensions, downrange and cross-range, are defined by the range and azimuth resolution of the radar sensor, respectively. The fine grid overlay represents the sampling resolution of the data acquisition system (DAS), which in every case exceeded the sensor resolution. DAS oversampling gave a constant data set resolution independent of the MMW sensor under test and provided additional sample points for averaging.

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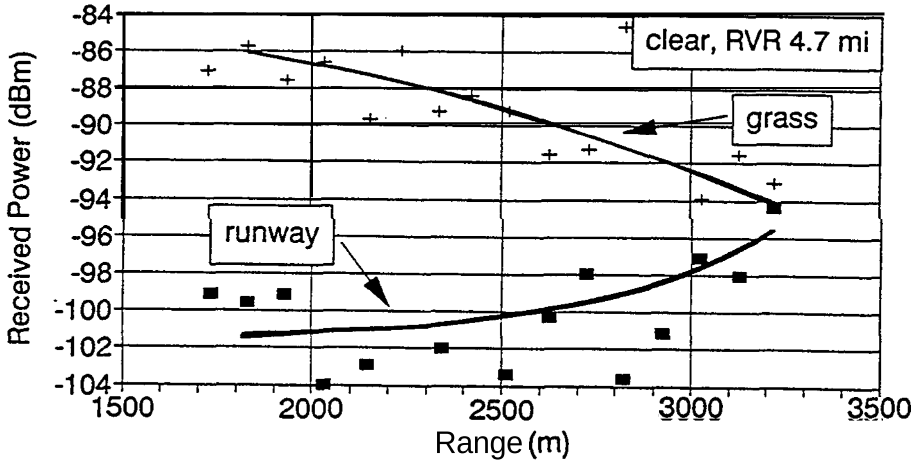


Figure 15a. 35 GHz Downrange Power Profile

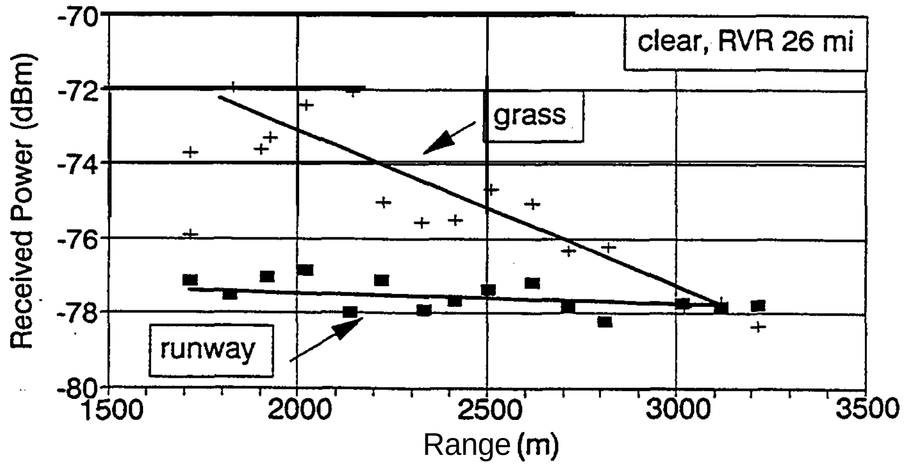
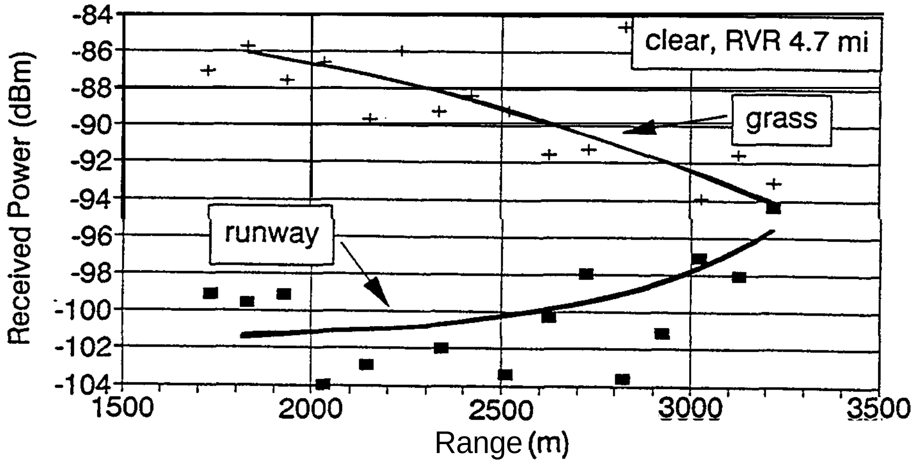


Figure 15b. 95 GHz Downrange Power Profile



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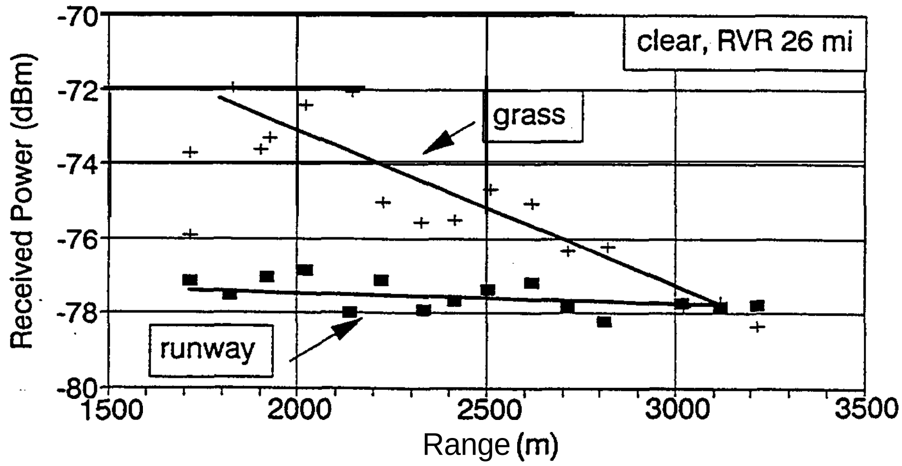

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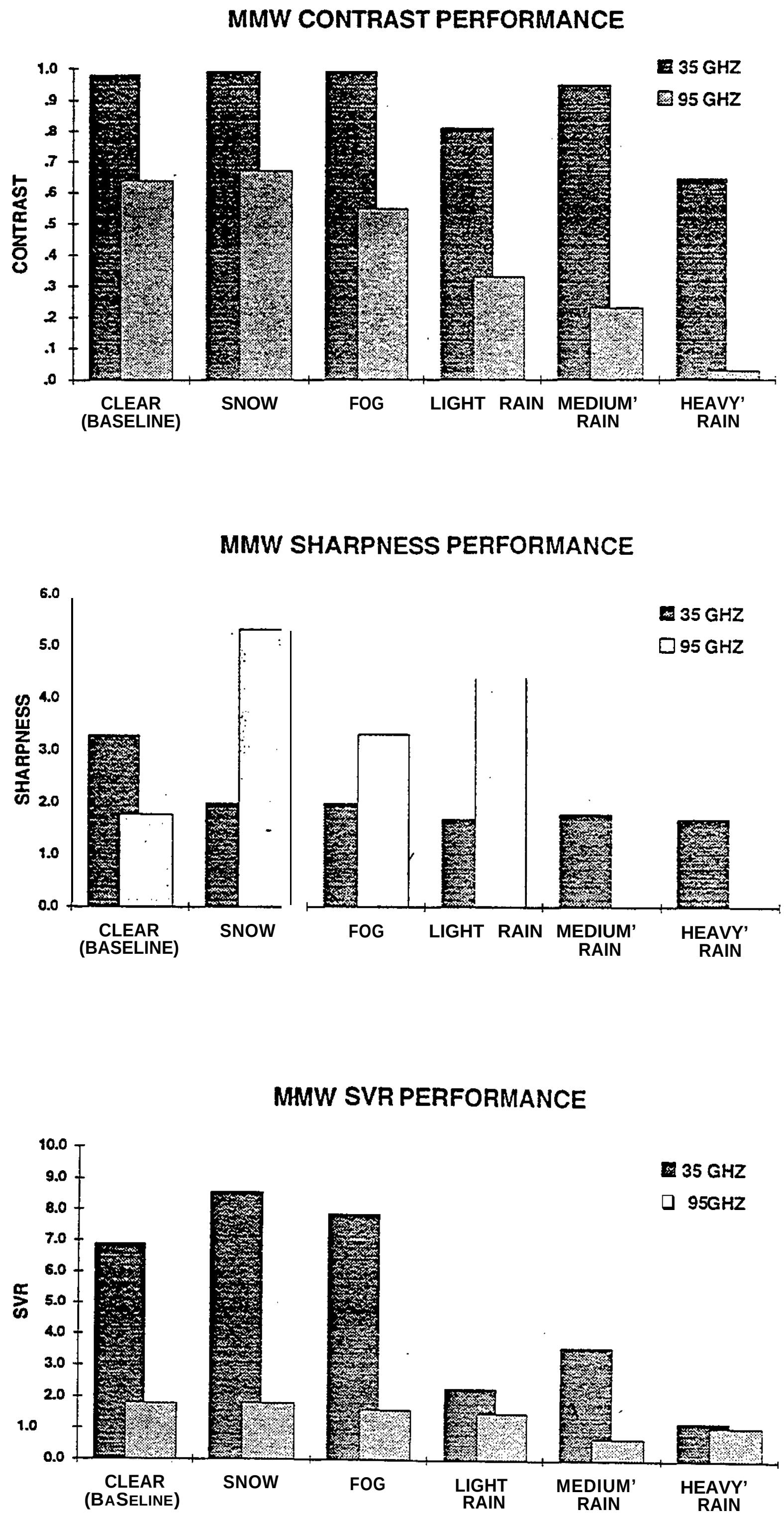

Figure 17. MMW Sensor Performance at 2 km in Clear Air, Fog, Snow, and Rain

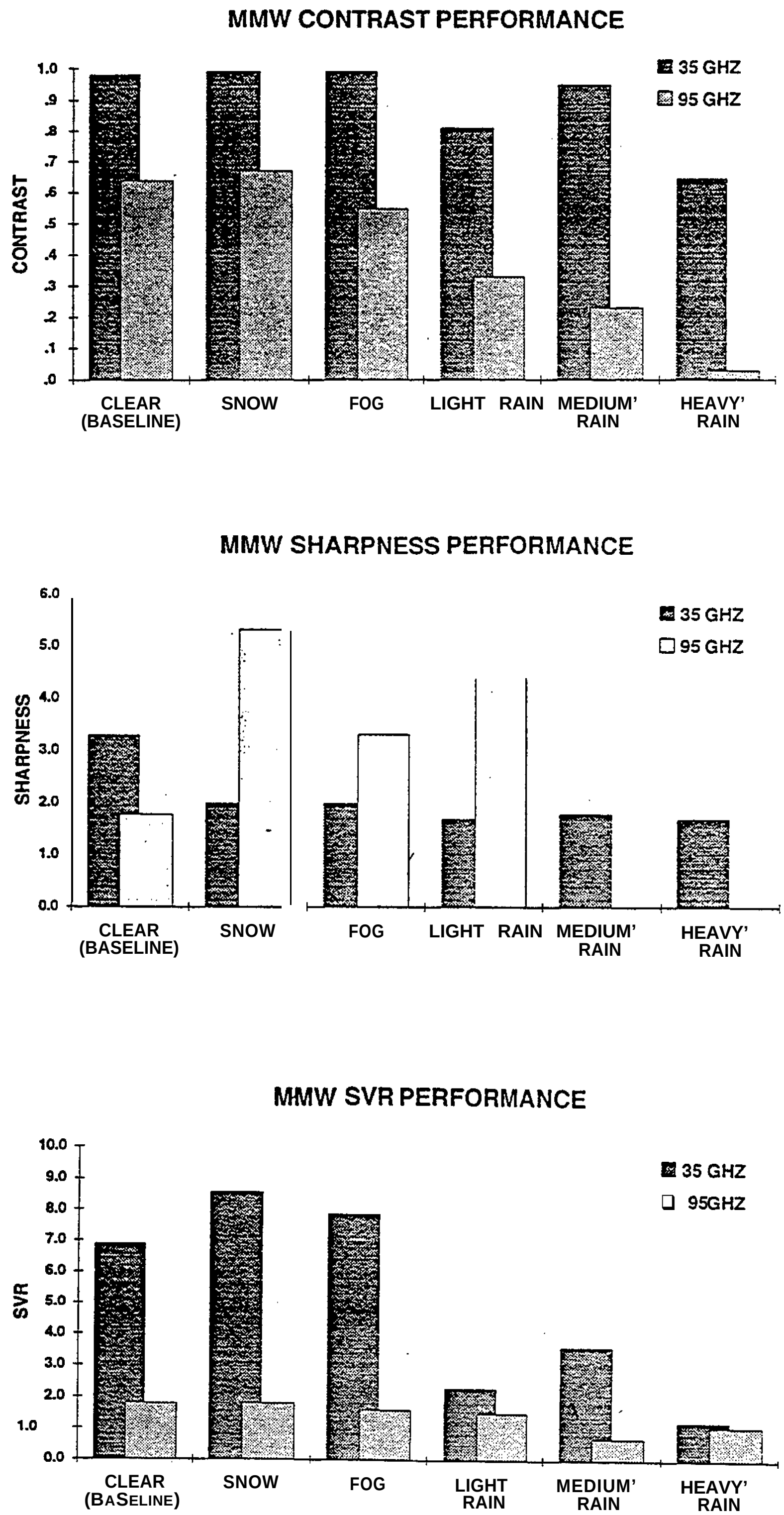

Figure 17. MMW Sensor Performance at 2 km in Clear Air, Fog, Snow, and Rain

Table 6. MMW Performance Summary At 2 Km Range

Meteorological Condition	Freq (GHz)	Contrast	SVR	Sharpness $(\deg^{-1})$
Clear (Baseline)	p i	high (-0.98)	high (6.9)	high (3.3)
		high (-0.64)	medium (1.8)	medium (1.78)
Snow		high (-0.99)	high (8.6)	medium (2.0)
	95	medium (-0.67)	medium (1.8)	high (5.33)
Fog	35	high (-0.99)	high (7.9)	medium (2.0)
	95	medium (-0.55)	medium (1.6)	high (3.33)
Rain (1.2 mm/hr)	35	high (-0.81)	medium (2.3)	medium (1.7)
	95	low (-0.33)	medium (1.5)	high (4.44)
Rain (5.3 mm/hr)	35	high (-0.95)	medium (3.62)	medium (1.8)
Rain (8.8 mm/hr)	95	low (-0.23)	low (0.7)	not measurable
Rain (12.9 mm/hr)	35	medium (-0.65)	low (1.22)	medium (1.7)
Rain (20.0 mm/hr)	95	low (-0.03)	low (1.08)	not measurable

3.3.6. Infrared Sensor Test Data Matrix

Baseline data were collected with the Kodak IR camera system on two occasions. The images were collected over a 24 hour period with nominally clear weather for both collection periods. IR data in low visibility conditions were collected on four separate dates. The low visibility weather conditions were nominally identified as rain with accompanying fog. The visibility on those data collection periods ranged from less than a kilometer to nearly 28 kilometers. Tables 7 and 8 summarize the IR data collected and analyzed.

Table 7. IR Image Data Collected At WPAFB 03/13/92 Through 05/28/92

	Date Collected	Number of Images
Baseline Diurnal	03/12/92	41
Fog / Rain	03/18/92	9
Fog / Rain	03/30/92	16
Fog / Rain	04/18/92	7
Fog / Rain	04/21/92	8
Baseline Diurnal	05/27/92	33
Total Number of Images		114

Table 8. IR I&age Data Analyzed

		Number Images Analyzed	Number with Runway Measurable
Baseline Diurnal	(03/13/92)	41	41
Fog/Rain	(03/18/92)	9	9
Fog/Rain	(03/30/92)	16	7
Fog/Rain	(04/18/92)	6	6
Fog/Rain	(04/21/92)	6	4
Baseline Diurnal	(05/27/92)	11	11
TOTALS		89	78
Total Number of Runway Radiance Measurements from Images			235

3.3.7. Infrared Sensor Baseline Performance

The contrast available in IR images collected during clear weather was observed to mirror the temporal variations in surface temperatures during the ‘diurnal periods in which

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Fog/Rain	(04/18/92)	6	6
Fog/Rain	(04/21/92)	6	4
Baseline Diurnal	(05/27/92)	11	11
TOTALS		89	78
Total Number of Runway Radiance Measurements from Images			235

3.3.7. Infrared Sensor Baseline Performance

The contrast available in IR images collected during clear weather was observed to mirror the temporal variations in surface temperatures during the ‘diurnal periods in which shows that the measured optical visibility is reduced primarily due to raindrop extinction and that the extinction due to fog particles is very small in all of the cases for which particle size data were available.

3.3.8. Conclusions Regarding SVS Sensor Tower Tests

3.3.8.1 MMW Sensors

All six of the MMW sensors tested at the tower facility were capable of imaging the airport runway scene in clear weather conditions. There were significant differences in the MMW imaging sensors' angular resolution, runway-to-grass contrast, signal-to-noise ratio, and maximum runway detection range. As would be expected from antenna theory, the 95 GHz radar sensors have more than twice the angular resolution of the 35 GHz radars for the same 30 inch antenna aperture. The differences in MMW radar RCS between the runway pavement and bordering grass areas at the 2° to 3° incident angle are about 16 to 22 dB. Resolution limitations of the MMW sensors prevented them from fully converting this RCS difference into image contrast. The 94-95 GHz radar sensors tested lacked the performance to image the runway out to the end at 3,300 m range. The 35 GHz radars exhibited higher signal-to-noise ratio, and were able to image the runway to 3,300 m range.

Meteorological effects of fog, snow, and rain decreased the maximum runway detection range for the MMW sensors by varying degrees. The MMW detection range was not significantly reduced by the snowfall and fog conditions that occurred during the tests. More MMW tower test data are needed in fogs of less than one mile visibility to establish any performance limitations due to fog. Rainfall rates as low as 2 mm/hr reduced the MMW detection ranges, especially for 95 GHz. Runway detection by the 35 GHz radars was seriously degraded for rainfall rates greater than 20 mm/hr. As was predicted from MMW propagation theory, the dominant effect of rain on image quality at ranges of 2 to 4 km is signal attenuation. The 35 GHz radar sensor tested provided the best runway detection performance in clear and adverse weather conditions with airport scene resolution adequate for the pilots' management of flight path to the runway.

3.3.8.2. Infrared Sensors

The dependence of IR contrast on ground surface temperature differences implies the dominance of the IR radiation emitted by the scene components which is a function of surface temperature and the emissivity of surface materials. Reflection of sources of illumination are important only for the solar disk and only at times when the sun is properly positioned. The shows that the measured optical visibility is reduced primarily due to raindrop extinction and that the extinction due to fog particles is very small in all of the cases for which particle size data were available.

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- Measure performance of the millimeter wavelength radar and its image processing under operational conditions.
- Measure performance of the forward looking infra-red sensor under operational conditions.
- Measure the actual weather conditions that the aircraft encounters when measuring the above phenomena and sensor performance.

- Determine, document, and correlate the actual weather conditions existing between the aircraft and the runway for all approaches in actual weather.
- Determine the image quality in a manner that can he correlated to achieved performance and is transferable to future synthetic vision systems.

Figure 18 illustrates the operational approach used in making the evaluation measurements listed above. They included :

- Manually flown precision approaches through the end of roll out or missed approach point.
- Manually flown non-precision approaches with a no-navaid final segment.
- Ground operations including taxi, roll out and takeoff.

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• Ground operations including taxi, roll out and takeoff.

Major Milestones. The following major milestones were established and accomplished during the System Integration, Evaluation and Demonstration task:

Program Milestones	
Milestone	**Date**
Task Accomplishment Plan	April 1991
Head-up Display Selection	April 1991
Radome Specification	May 1991
Experimental SVS Requirements Study	June 1991
Simulation Requirements	June 1991
Aircraft Selection	July 1991
Preliminary Design Review	July 1991
Critical Design Review	Nov/Dec 1991
Program Plan	February 1992
35 GHz. Radome Available	February 1992
Hot Bench Integration and Test	February 1992
Flight Test Plan	March 1992
Safety Plan	March 1992
FAA Experimental Certificate	March 1992
Flight Readiness Review No. 1	April 1992
Suitability Flights (35 GHz.)	May 1992
Evaluation Flights (35 GHz.)	July 1992
Flight Readiness Review No. 2	August 1992
FAA Waiver To CAT IIIa	August 1992
Suitability Flights (94 GHz,)	October 1992
Continue Eval. Flights (35 GHz.)	November 1992
Final CIST conference Meeting	January 1993
Final Report	February 1993

3.4.1. Description Of Experimental System

The experimental Synthetic Vision System consisted of 1) MMW and FLIR Sensors, 2) Head Up Display, 3) Weather Acquisition Sensors, 4) Aircraft, and 5) Data Acquisition System. The experimental system incorporated all the functions in prototype form necessary to support the variety of operational approach and landing procedures to be demonstrated and evaluated. The system was often referred to as the Functional Prototype Synthetic Vision System (FPSVS)

3.4.1.1. Sensors

The experimental system used three sensors; the Honeywell 35 GHz MMW Sensor, the Lear 94 GHz MMW Sensor, and the Kodak 3-5 micron FLIR. These sensors provided an opportunity to examine a wide range of sensor technology.

3.4.1.1.1. Primary MMW Sensor

Described briefly earlier in this Executive Summary, in the overview of sensor tower testing, the 35 GHz sensor system was developed for this SVS Technology Demonstration Program by the Honeywell System Research Center using an existing receiver /transmitter unit developed several years earlier for another application. An electro-mechanical scanning antenna was developed specifically for the SVS application by Malibu Research Associates under contract to Honeywell. An illustration of the installation of this sensor in the radome of the flight test aircraft is provided in Figure 19.

A shaped reflector was used to achieve a vertical fan-beam pattern of approximately 26 degrees with cosecant squared rolloff, and an azimuthal beamwidth of 0.7 degrees. Based on an "Eagle Scanner" technique, a dielectric slug was used to change the phase velocity of the waveguide feed, scanning 30 degrees in the horizontal plane at approximately 10 Hz. An image processor performed the trigonometric conversion from range-azimuth to elevation-azimuth to produce the conformal image. Conformality was also maintained during platform motion. Platform altitude, pitch, and roll information were required by the processor to perform the conversion and stabilization.

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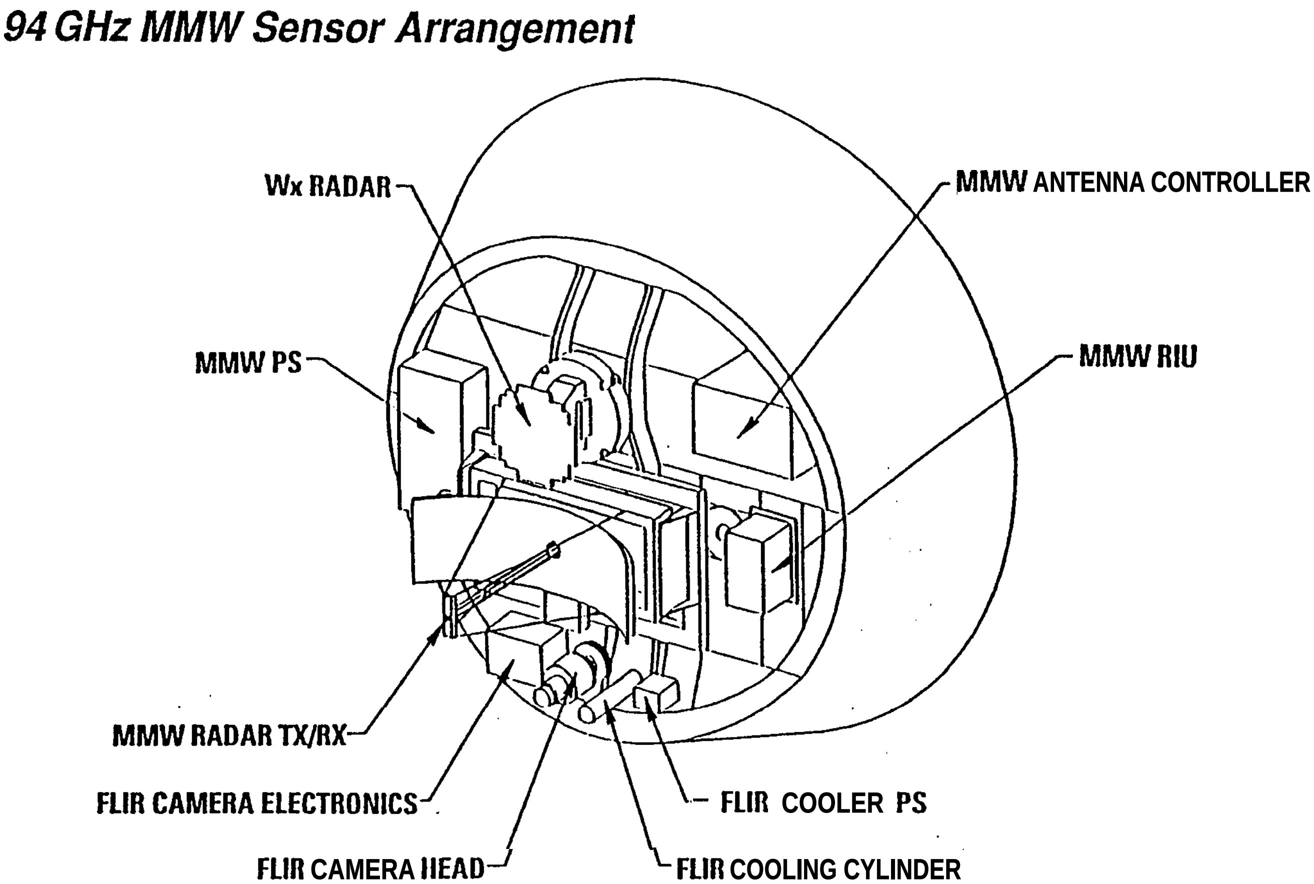
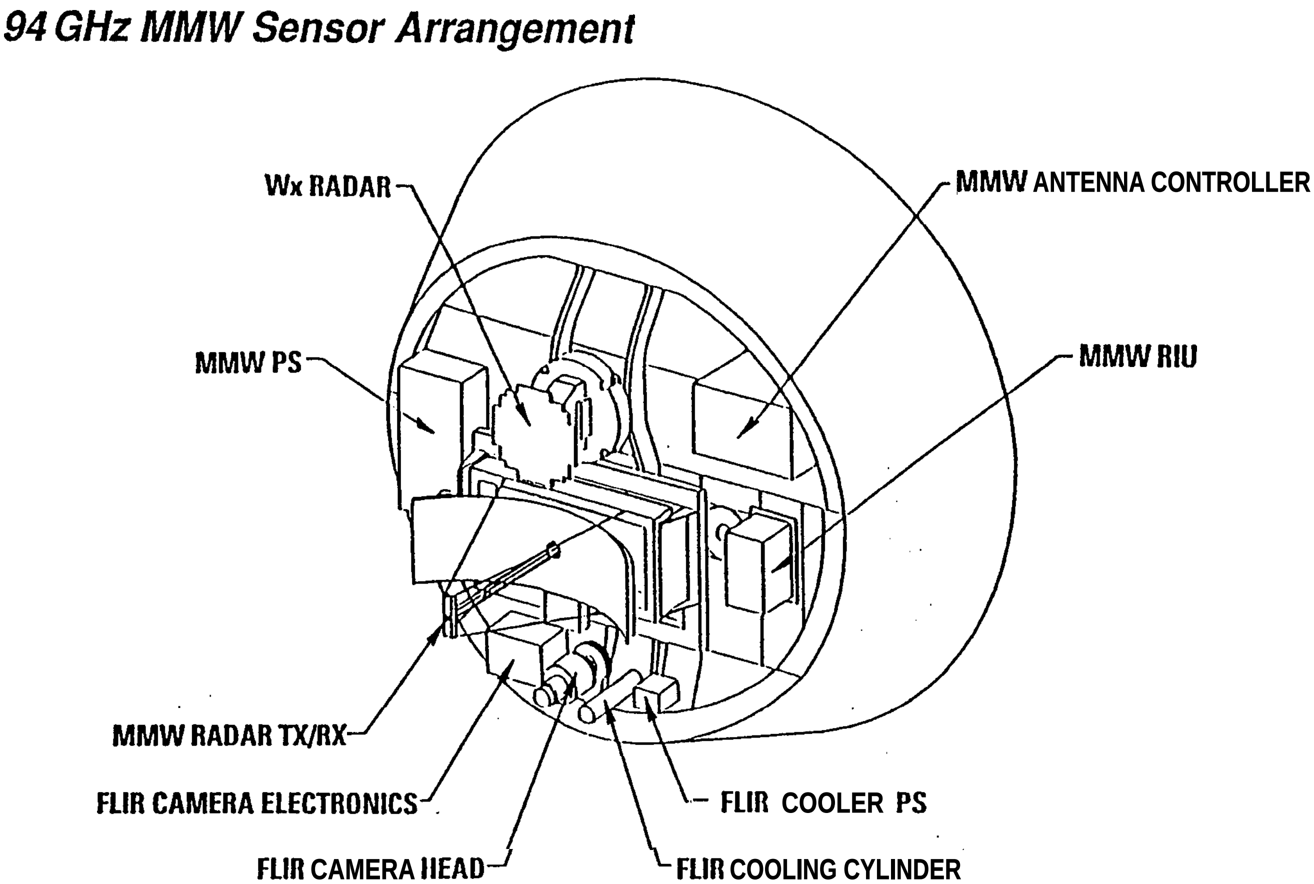


Figure 20. 94 GHz Sensor Installation in Test Aircraft

An image processor performed the trigonometric conversion from range-azimuth to elevation-azimuth to produce the conformal image. Conformality was also maintained during platform motion. Platform altitude, pitch, and roll were required by the processor to perform the conversion and stabilization.

3.4.1.1.3. 3-5 Micron Forward Looking Infrared (FLIR) Sensor

A Kodak FLIR Camera, model KIR-310 series 200, was used to produce an IR image. This sensor was also designed as a part of the competitive design study carried out separately from the SIED Task. This design was then built by Kodak for another customer and for other purposes but was subsequently provided by Kodak for use in the SIED Task. The location of this sensor in the radome of the test aircraft can be seen in Figures 19 and 20.



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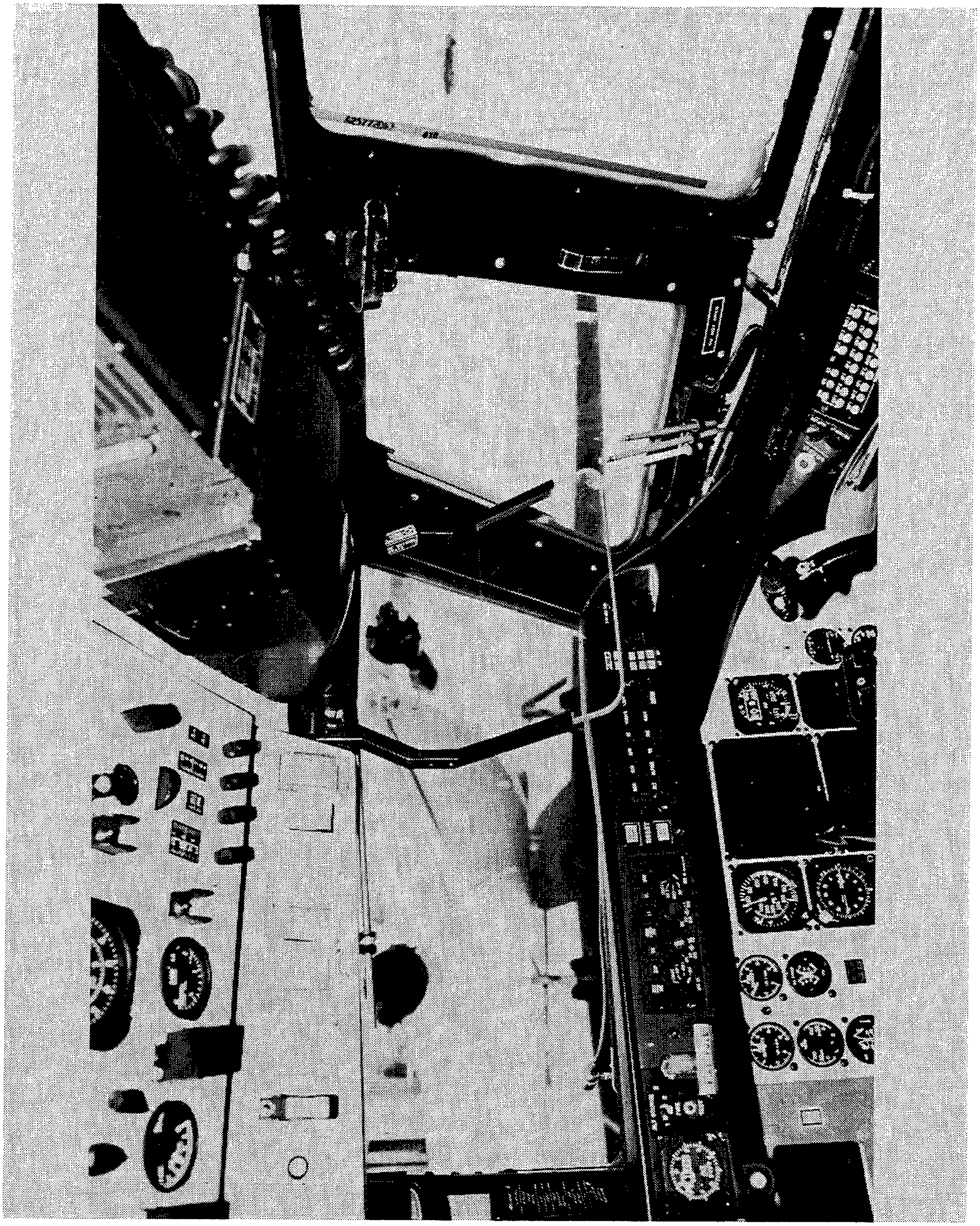


Figure 21. GEC Head-Up Display Installation in SVS Test Aircraft

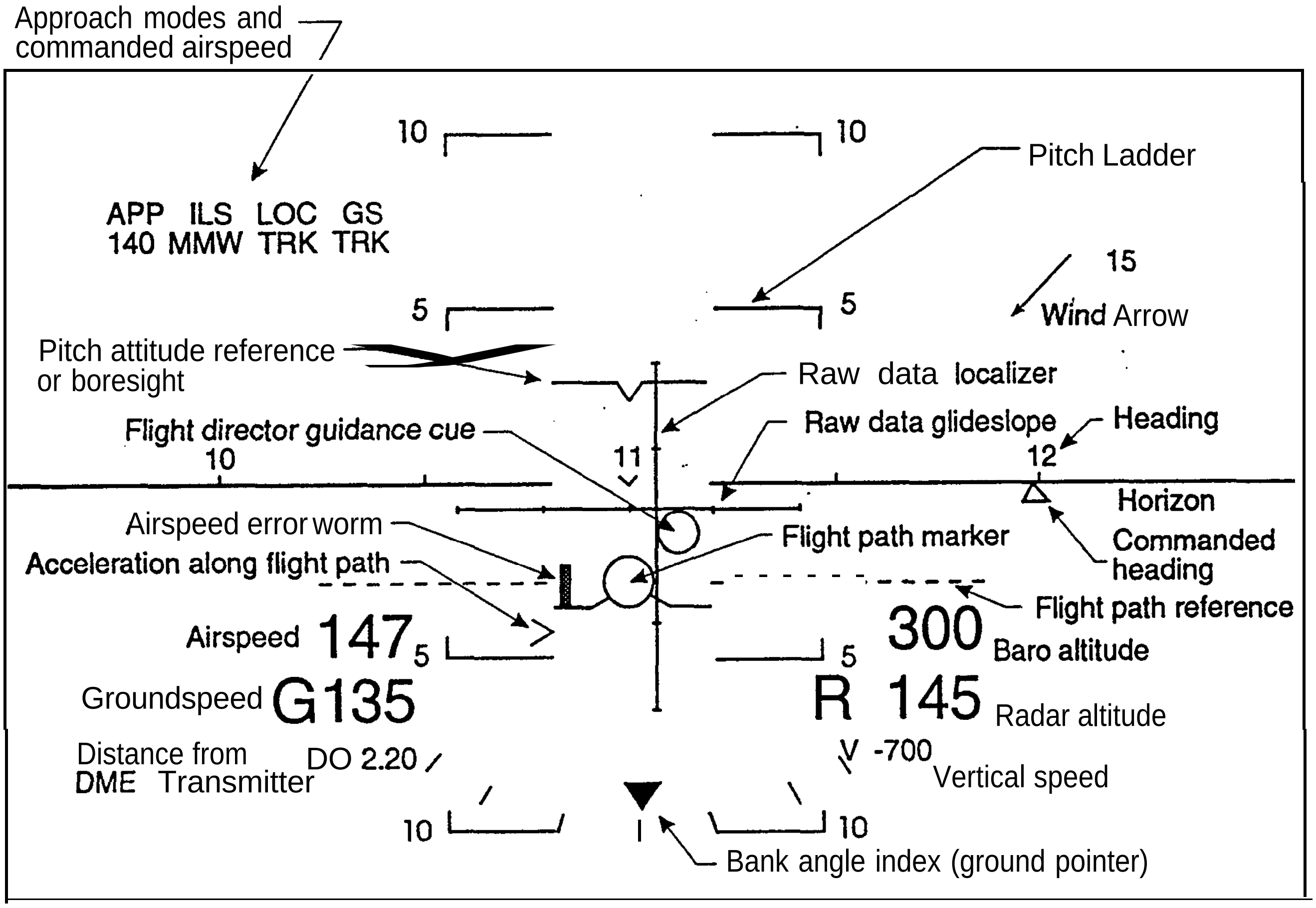


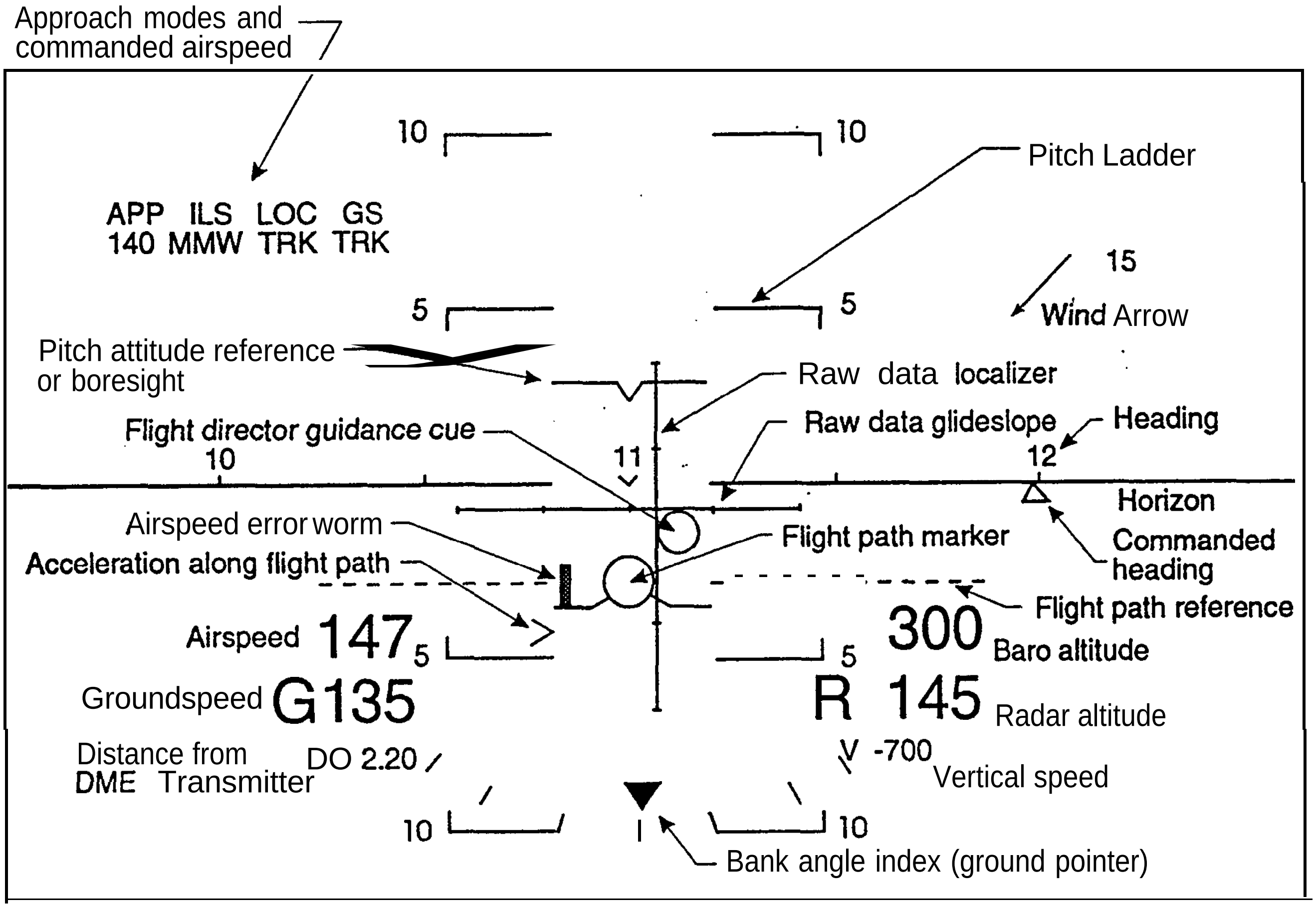
Figure 22. Head-Up Display Symbology Used in SVS Test Aircraft

based on recommendations from an SAE subcommittee on HUD symbology, and on opinions of engineers at GEC.

The flight director guidance laws were developed by Hoh Aeronautics, Inc., under contract to TRW. These control laws were adequate to accomplish the approach task in significant winds and wind shear and provide flare guidance that was considered adequate by the pilots. However, the laws would have to be futher refined before they could be certified for flight in all operational conditions, especially for the localizer and glideslope capture functions.

3.4.1.3. Weather Sensors

The aircraft was equipped with three weather sensors; two wing mounted probes and one fuselage mounted probe. The wing mounted pods could carry interchangeable particle measurement laser probes. The fuselage probe measured liquid water content. The laser probes



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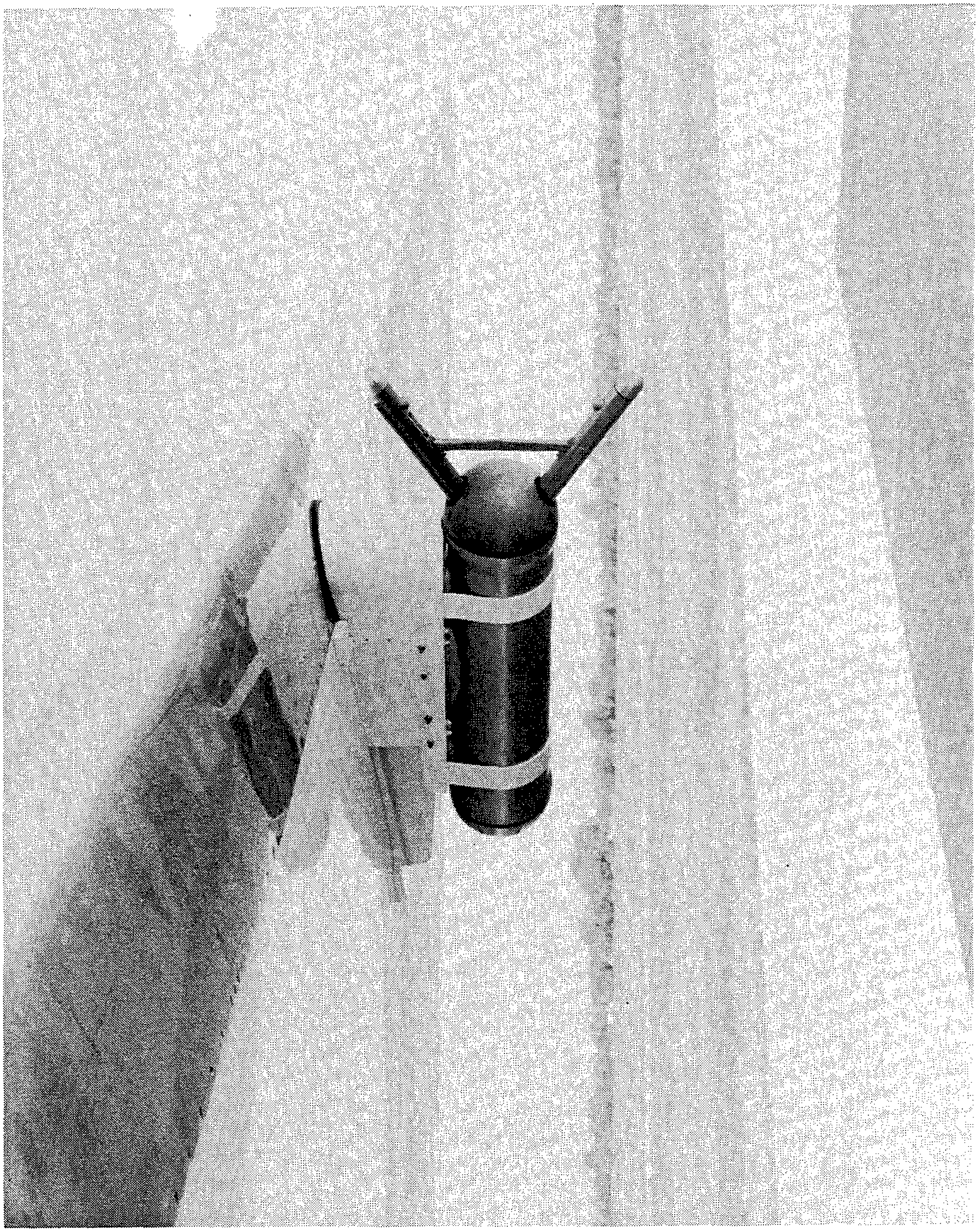

Figure 23. Precipitation Measurement Probe Mounted On SVS Test Aircraft

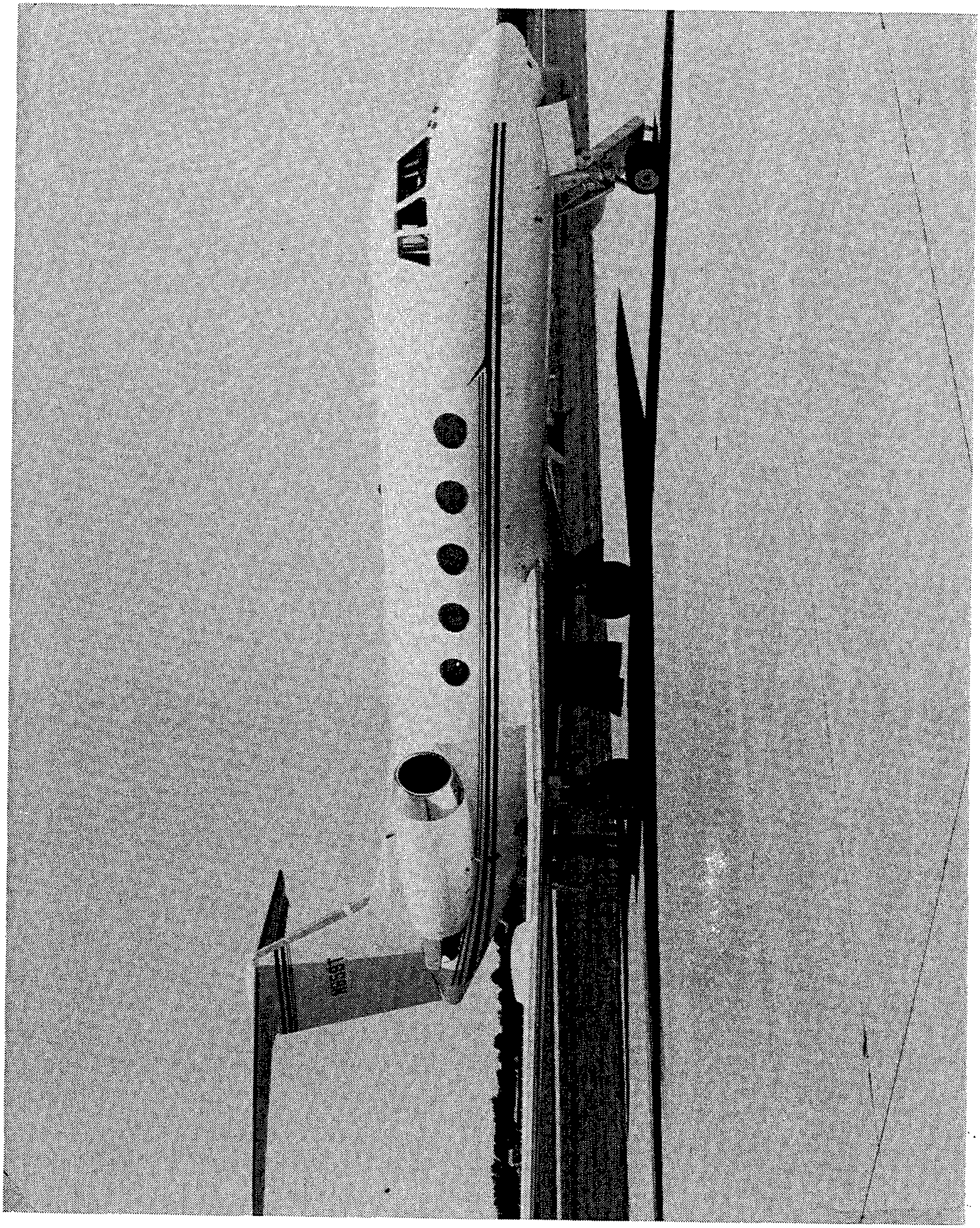

Figure 24. SVS Test Aircraft

3.4.1.4.2. Special SVS Aircraft Features

The aircraft was modified to accommodate the following features designed specifically for the SVS Functional Prototype System (FPSVS):

Special Antennas The MMW and FLIR sensors required more space than was originally available. Several modifications had to be performed to the nose area. The ILS glideslope antenna was replaced with a conformal antenna and relocated at the bottom of the radome., the ILS localizer antenna was relocated to the fuselage, and the existing 15" Weather Radar Antenna was replaced with a smaller 12" model and moved up. An external VHF Communications antenna was added to the rear bottom of the fuselage. The antenna was connected to a portable hand held radio located

in the cabin at the Test Directors Work Station The radio was operated in the cabin by the Test Engineer. Antenna Specifications can be found in appendix C VHF Communication Antenna.

Yoke Position Transducers. Position transducers were added to the test pilot's yoke (right seat). The transducers (pitch and roll) was designed to provide a resistance which was linearly proportional to the yoke position. This position data was recorded by the Data Acquisition System (DAS).

Sensor Selector. A left thumb switch was placed on the right seat yoke. The push button switch was used by the pilot to rotate between the MMW image, FLIR image, and no image on the HUD.

Event Marker. A right thumb switch was placed on the right seat yoke. The thumb switch was used by the pilot to record an Event Mark on the Data Acquisition System.

Dual-Circuit Intercom. The es tir g aircraft intercom and Public Address System was enhanced with a se :ond cabin intercom . The enhanced intercom system provided each of the FPSVS Engineering crew (Test Direc Test Engineer, MMW Sensor Engineer, Host/Wx, and Observers (Qty 4)) with a headset ano ..icrophone. The intercom was based on a "Hot" Microphone. For safety, the installation was designed so that the pilot/copilot was able to address the support crew over the existing PA s ee audio outputs were routed to the DAS for audio recording.

Radome Air Purge. Pressurize ' dry cabin air was vented into the radome . The cabin air reduced the moisture c ntent within the radome. The purpose of the vent was to prevent condensation on the FLIR window, waveguides, and the non-sealed FPSVS components. The vent remained open for altitudes below 10,000 feet.

Power Converters/Inverters The aircraft contained special power generators, converters/inverters, and transformer rectifiers. The Power Supplies provided clean regulated power to the FPSVS equipment.

Circuit Breakers The FPSVS Equipment contain a hierarchical 2-level circuit breaker system. The first level was located in the rear baggage compartment of the aircraft. This panel contained individual circuit breakers for each rack, and each type of power within each rack. These circuit breakers were rated slightly above the maximum required current. The next level circuit breakers were at the back of each rack. These breakers were rated at a higher current level but had a faster response time (short circuit protection).

External Ground Power. Provisions were made to use an external AC power cart. The ground cart provided 3 phase 115 VAC 400 Hz power to the FPSVS.

Monitor Points. Electronic interfaces to the existing aircraft avionics were installed and connectorized. This permitted connections to be made easily between the FPSVS and the avionics. These connectors also permitted the Hot Bench computer to bypass the aircraft avionics and emulate all the required signals for the FPSVS.

Sensor Mounting Bracket. A "Universal" Mounting bracket was installed on the forward bulkhead located within the radome space. Special signature brackets were designed for the Honeywell Sensor, Lear Sensor, and Kodak Sensor. The signature brackets held each sensor; and mounted directly to the universal bracket.

HUD Combiner Camera. A HUD Combiner video camera was developed to record the HUD Combiner image (as seen by the pilot). The camera was located between the combiner glass and the pilot's eye. As such the camera was able to see the HUD image and the outside world. This camera was used to record contrast shifts (due to ambient light), runway edge problems and image registration with the outside world.

Glareshield Camera. A glareshield video camera was mounted to provide an out the window view of the approaches and taxi. The color camera provided a real-time image of the approach. The image was available to the cabin monitors and was recorded on the VCR.

Equipment Racks. Nine 5 foot high 19" equipment racks were installed in the aircraft. to hold the experimental SVS equipment and data monitoring and acquisition equipment.

Head Up Display. The **HUD** Overhead Unit was mounted above the right seat. A second tray was installed above the left seat (transfer between the trays required approximately 10 minutes).

Head Down Display. A Head Down Display was centrally installed on the cockpit panel. The display was mounted in place of the center tube of a 5-tube Honeywell EFIS system.

Wing Mounted Weather Pods. The aircraft was required to carry two weather probe pods in a free air stream. The two interchangeable pods, provided by Particle Measurement Systems, were mounted on each wing. Each pod was held stable beneath the wing using dedicated pylons. These pylons were designed to carry a single pod each of approximately 45 lbs at a maximum aircraft speed. The pylon was designed to allow a quick removal and installation of the pod.

3.4.1.5. Data Acquisition System

The Data Acquisition System (DAS) was designed to record and reduce flight data for the evaluation flight test. The recorded information consisted of aircraft avionics, video, internal MMW, and weather parameters. There were four major airborne acquisition categories and three major ground analysis categories. The reponsibilities for each of the four data acquisition systems is outlined below:

Location	Purpose	Responsibility
Airborne (Acquisition)	System Data	TRW
	Weather	JTD
	MMW (Primary)	Honeywell
	MMW (Secondary)	Lear
Ground (Reduction/Analysis)	System Data	TRW
	Weather	JTD
	MMW (both)	GTRI

3.4.2. Description of Primary Test Airports

A description of the primary airports used during the testing is provided in Table 10. With the exception of San Diego, all of the runways were surrounded by grass. In some cases, the primary runway surface had a different texture than the sides, where the runway lights were installed. For example, Los Angeles had a concrete runway with asphalt sides. In other cases, the sides of the asphalt runway were also asphalt, but the surface was not as well maintained as the runway itself, and had a rough appearance.

3.4.3. Ground-Based Simulation

A fixed-base simulation of the synthetic vision HUD display was developed by the Douglas Aircraft Company under contract to TRW. An existing MD-11 cockpit and math model was used as a starting point. A GEC HUD was installed in the cockpit in a configuration identical to that of the G-II flight test aircraft. This HUD was capable of providing superimposed stroke and raster information. The software supplied by GEC for the HUD was identical to that used in the flight test. The raster display on the HUD was capable of simulating a FLIR scene and a MMW scene. Since these were developed before the flight testing it was necessary to estimate the FLIR and MMW sensor performance characteristics. All the evaluation pilots agreed that the raster scene displayed during the simulation was reasonably representative of the results obtained during the

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The simulation included a Redifon camera-model type Visual Flight Attachment (VFA). The model runway was 10,400 feet long, 200 feet wide and included approach lights, strobes, runway end markers, threshold bars, touchdown zone, VASI, edge lights, and centerline lights. This VFA system was capable of simulating varying runway visual range and ceilings. It was set up to perform approach, landing and takeoff operations in Cat I, Cat II, Cat IIIa, and Cat IIIc conditions. Steady winds, wind-shears, crosswinds, and turbulence were simulated to assist in the development and evaluation of the flight director laws and to provide pilot training for the flight test program. The cockpit was configured like an MD-l 1 with six across 8x8 inch fully operational CRT displays. The Electronic Display formats were modeled after the MD- 11. The MD-l 1 autopilot was operational, and was frequently used for demonstration flights.

The objectives of the simulation were to:

- Evaluate and refine the HUD symbology and flight director guidance laws
- Familiarize the evaluation pilots with the HUD symbology and SVS procedures. Also develop SVS procedures where necessary
- Provide familiarization for demonstration pilots

Some changes were made to the HUD symbology as a result of the initial evaluations by the evaluation pilots. The primary change was in the flight director guidance laws. These were modified considerably from the initial configuration, and the simulation was used extensively to accomplish the necessary fine tuning. Even though the laws were tuned for the MD-11 aerodynamics, they were found to work acceptably well on the G-II without modification.

A number of demonstration flights were made to key members of government and industry. In most cases, the demonstration pilots were given a simulation session to gain familiarity with the HUD symbology.

3.4.4. Test Plan and Priorities

The detailed test plan used to guide the flight testing is included in Volume 4 of this report. The waiver issued to the project by the FAA to permit descents to below CAT I minimums is also included in Volume 4. The five selected airports were Arcata, Santa Maria, Vandenberg AFB, Santa Barbara, and Point Mugu NAS, all in California. The test aircraft was operated out of Van Nuys, California within a reasonable flying time of the five approved airports. A list of prioritized test objectives from the test plan is given in Table 11, along with what was done to accomplish the objectives. The test objective priorities were established by the test team based on inputs from the Certification Issues Study Team.

Table 11. Summary of Project Objectives and Accomplishments

Priority	Objective	Accomplishment
1	Low visibility approaches to Cat IIIa minimums in actual Cat IIIa conditions.	37 approaches in actual Cat IIIa conditions of which 12 were to Cat IIIa minimums. Some approaches were not conducted to the Cat IIIa DH because the airport was not included in the waiver, or because the waiver had not yet been issued
2	Accomplish the above approaches in different types of fog	Approaches were made in coastal fog (Arcata, Santa Maria, and Vandenberg), in valley fog (Huntington WV), and in frontal fog (Worcester, MA).
3	Conduct approaches in rain with varying rain-rates	Approaches were made to five different airports in rain with rain-rates varying from 0.50 to 22 mm/hr.
4	Conduct approaches to different types of airport surfaces	Approaches were made to 27 different airports. Formal evaluations were made during approaches to 17 of these airports.
5	Conduct landings in simulated Cat IIIc conditions (i.e., simulated O/O)	All three evaluation pilots successfully accomplished three simulated 0/0 landings and roll-outs. Simulated O/O takeoffs were also accomplished
6	Test ability to identify runway incursions using the MMW sensors	Six runs were made in simulated IMC conditions where runway and taxi way incursions were staged. The evaluation pilot did not know in advance when these incursions were to be staged
7	Test a second MMW radar at 94 GHz	The Lear 94 GHz MMW radar was installed, checked out, and 11 final suitability runs were made
8	Test an infrared sensor in actual weather	A Kodak 3-5 micron FLIR was installed and was operational in all actual weather runs.
9	Conduct approaches in snow conditions	Approaches were made to Pueblo Colorado in falling snow, with 1 to 2 inches of wet snow on the runway, and to Pueblo and Colorado Springs to a plowed runway
10	Test ability to conduct non-precision approaches to simulated Cat IIa minimums	Localizer approaches and no-navaid-final-segment approaches were flown to simulated Cat IIIa conditions

IMC conditions were simulated by inserting a cardboard shield between the HUD and windscreen. The shield was held in place with Velcro tape, and was removed by the Test Director at the appropriate decision height. In the case of simulated Cat IIIc (0/0) landings, the shield was not removed throughout the approach, landing, and rollout. The safety pilot typically took over control of the aircraft below 60 knots as he had control of the nosewheel steering. For some runs, the shield was removed at 50 feet altitude to simulate Cat IIIa, and was reinserted during the rollout to simulate a surprise fog bank encounter.

3.4.5. Evaluation Pilots

Three evaluation pilots participated in the flight test program for purposes of taking data. The pilots were carefully selected so as to bring to the tests a cross section of experience including extensive airline experience, military transport, fighter, and helicopter experience, FAA certification experience, and professional flight test backgrounds that included use of head-up displays. All three of the pilots were type rated in a number of transport category aircraft. Two of the pilots were Douglas Aircraft Company experimental flight test pilots and participated as part of their employment by Douglas; a third pilot was an FAA experimental flight test pilot and certification pilot who participated as part of his responsibilities to the FAA Transport Aircraft Certification Directorate.

Training for the evaluations in the G-II aircraft was accomplished in two phases. First, all of the evaluation pilots attended simulation and ground training to qualify as second-in-command in the G-II aircraft at Simuflight in Dallas Texas. Second, a fixed-base simulator was modified by Douglas Aircraft to include the GEC HUD used for the SVS program. Models of the millimeter-wave radar and forward looking infrared sensors were included in the simulation, and were superimposed on the stroke symbology on the HUD. The simulation was used to optimize the HUD symbology, refine the flight director control laws, and to accomplish pilot training.

3.4.6. SVS Instrument Approach Procedures

For the most part, the instrument approach procedures used in the flight tests were conventional. Specialized procedures were employed to ensure safety, and to obtain data. The evaluation pilot was required to make three callouts unique to the SVS program.

- Radar Image - This callout indicated that the pilot could see a pattern on the HUD that signified that the radar was imaging the ground
- Runway Image - This was a highly significant call. It indicated that the evaluation pilot had an image of the landing runway, and that the quality of the image was sufficiently good to continue below Cat I minimums on a Type 1 beam, with no transmissometers (RVR data), and no touchdown zone or centerline lights. The safety pilot was required to execute a missed-approach if he did not hear the "runway image" call before reaching the published decision-height for the approach.
- Visual-Land - This was also a highly significant call in that it indicated that the pilot had a view of the runway environment that was sufficient to continue to landing without synthetic vision. The safety pilot was required to execute a missed approach if he did not hear the "visual land" call above the SVS DH for the five airports on the waiver, and the published DH for all other airports. The SVS DH was always 50 feet.

In addition to the above calls, the Test Director was required to monitor the radar and barometric altimeters approaching the Cat I decision-height. If the radar altimeter indicated the proper trends approaching DH, the test director called "altimeters verified". The safety pilot was required to execute a missed approach if he did not hear this call for approaches in weather below Cat I minimums. The purpose of this procedure was to limit the exposure time over which the single radar altimeter could fail with significant consequences. The probability of such a failure was calculated to be less than 10^{-6}, a value felt to be adequate for the test environment by the flight safety review board.

Three types of approaches were made during the flight test program; the normal ILS, a non-precision localizer approach, and a no-navaid-final-segment approach. These are illustrated in Figure 24. For the ILS approaches, the evaluation pilot tracked the flight director down to the Cat IIIa decision-height of 50 feet. The image was primarily used to monitor the approach, although it was common for the evaluation pilot to use the image for runway alignment when the integrity of the localizer was questionable. For the non-precision localizer approach, the normal procedure was used for the descent to the minimum descent altitude (MDA). A descent below the MDA was initiated after the pilot made the "runway image" call. Lateral control was identical to the ILS whereas longitudinal flight path control depended on the image and the HUD symbology. The flight director guidance cue was in a mode to provide only altitude hold or vertical speed hold for non-precision approaches, and the raw-data glideslope information was not displayed on the HUD. The no-navaid-final-segment approach was conducted in an identical fashion to the localizer approach except that the test director detuned the ILS localizer frequency after hearing the pilot call "runway image". This required the evaluation pilot to rely only on the HUD image and symbology (without flight director or ILS guidance) for guidance . The safety pilot always had full ILS glideslope and localizer information on his displays. For most simulated IMC approaches the cardboard shield was in place in front of the HUD down to an altitude of 50 feet, A few ILS approaches were conducted to Cat IIIc (O/O) minimums, and a few were conducted to Cat II (100 ft DH) minimums.

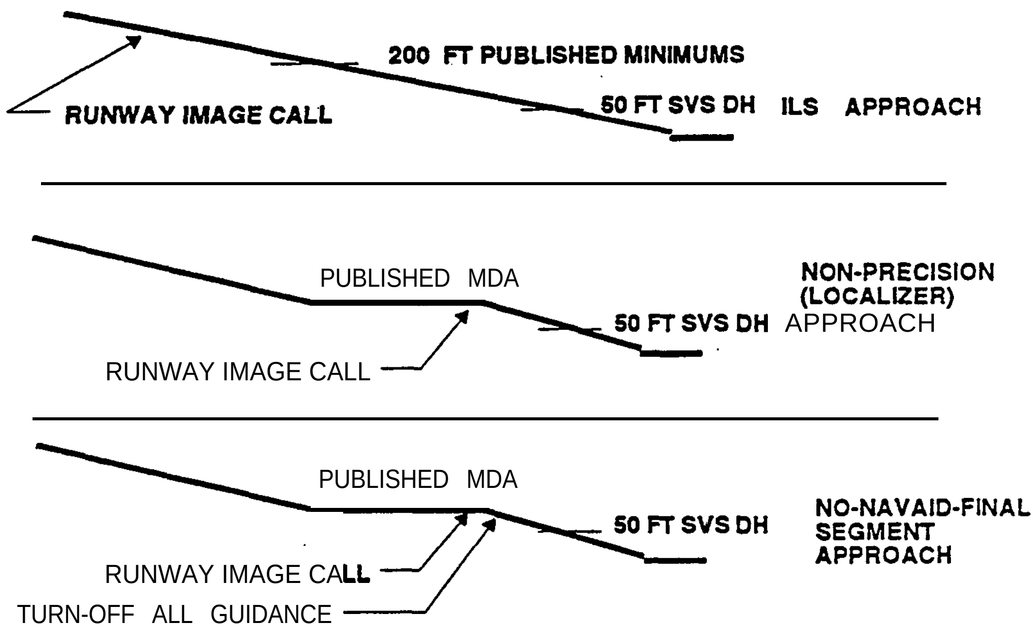

Figure 25. Approach Procedures Used in Flight Test Program

3.4.7. Sensor Performance In Flight

An assessment of the performance of the sensors was conducted by GTRI as a part of the SEID Task. This assessment was performed primarily to establish a clear understanding of the contributions of the sensors to the image used by the pilots and to the overall system performance.

3.4.7.1. Radar Sensor Performance Characteristics Measured In Flight

In performing this assessment, GTRI used many of the same techniques for characterizing the performance of the sensors that were developed in the tower test of the sensors. Also, in many areas, the analyses of the performance of the sensors incorporates information gained in the complementary studies performed in the tower facility.

Figure 26, an illustration of radar phenomenology used previously in this report in the discussion of testing of the SVS sensors in the tower facility, is used again to illustrate a hypothetical runway surface and the surrounding terrain as a radar might view them.

Figure 27 illustrates the radar signature expected for the runway-terrain scenario. The oval in this figure contains seven constant-range cross-sections from the return signal a radar might receive when viewing the airport scene. Note the left and right transitions in the signals corresponding to the boundaries between the higher-amplitude terrain returns and those of lower-amplitude from the runway. If the seven constant-range cross-sections of Figure 27 were to be averaged(along each azimuth line), a composite waveform would be derived which could be analyzed as illustrated in Figure 28. Because of its general shape, the plot of this waveform is referred to as a “gutter” plot.

Three parameters can be defined using the gutter plot which it was felt might be useful in characterizing how well the runway can be distinguished from the surrounding terrain. <u>Contrast</u> is a function of the average signal level received from the runway relative to that received from the surrounding terrain.

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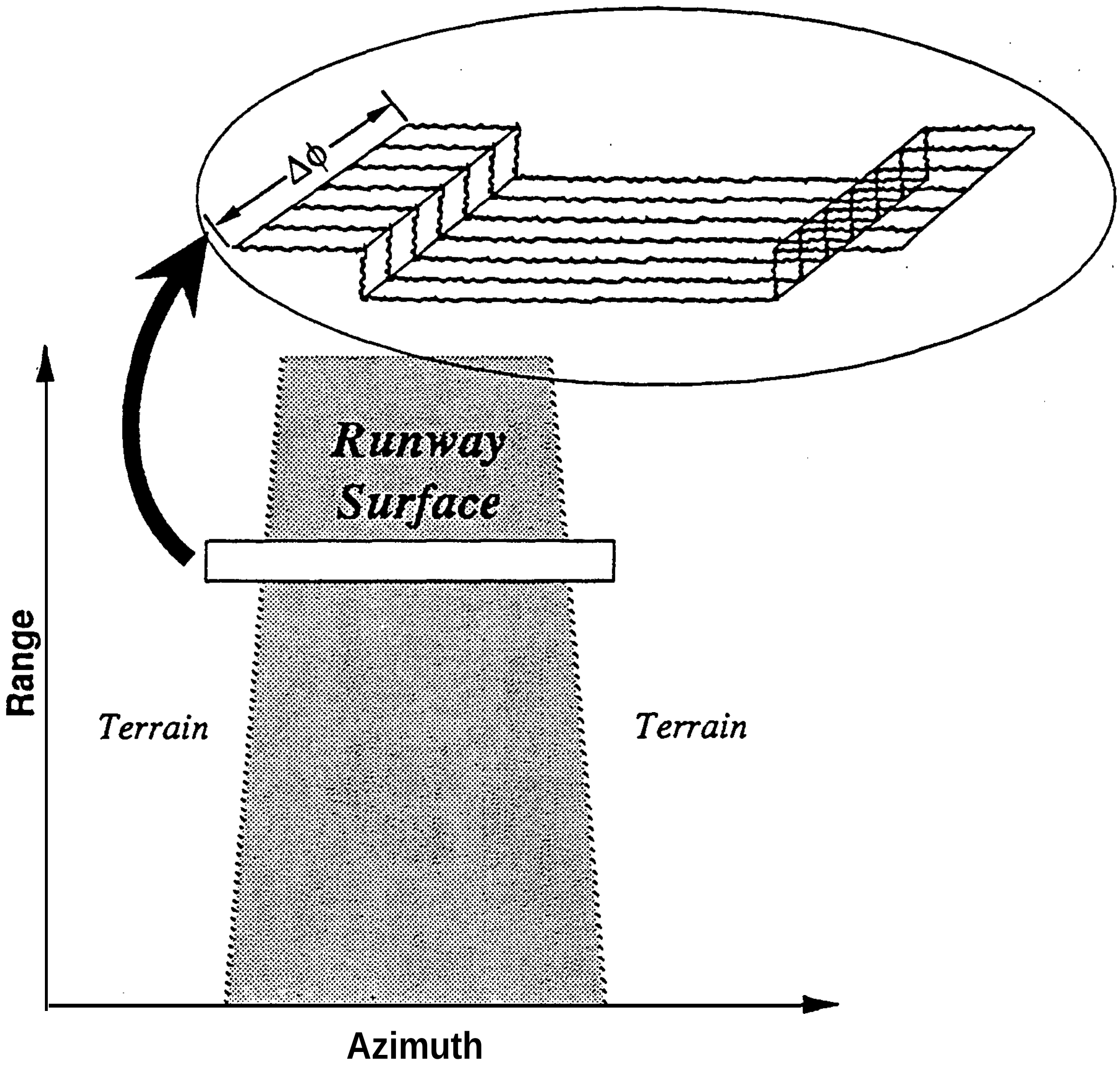

Figure 27. Illustration of Basic Radar Signature for Runway-Terrain Scenario

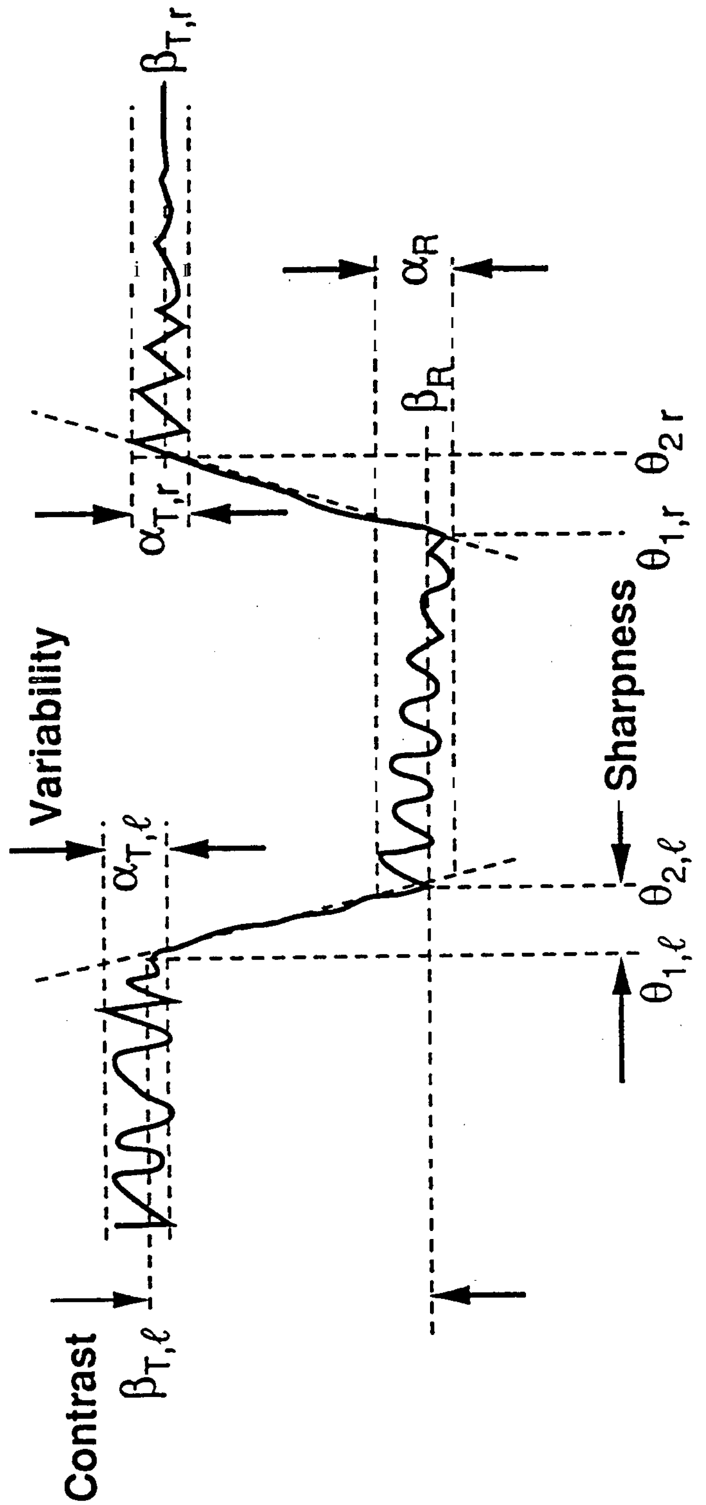

Figure 28. Illustration of Simple Gutter Plot with Basic Image Quality Metrics Indicated

Intuitively from Figure 28, the contrast improves as the terrain brightness becomes increasingly larger than the runway brightness.

The notion of sharpness is also illustrated in Figure 28. Sharpness is defined as the inverse of the angular extent in azimuth over which the low-to-high or high-to-low transition occurs. If these angular extents are very small, then the transition will be clear and distinct and can be identified easily by the pilot. And since sharpness is inversely proportional to the angular transition, larger sharpness values are desirable.

The final parameter illustrated in Figure 28 is variability, which is a measure of the standard deviation of the radar signal amplitude. For a waveform such as that shown in Figure 28, there are three variability measures - one for each side of the terrain and one for the runway. Large variability's correspond to "noisy" or "spiky" return signals which can mask actual surface transitions or be taken to falsely represent surface transitions not present in the scene.

This definition of variability is closely related to the term speckle noise, which is used to describe the random variations seen in signals returned from nominally homogeneous areas, such as a section of asphalt pavement, or a patch of uniform grass. While large amounts of speckle noise within an image will certainly be distracting to the pilot, smaller amounts should be tolerable, and may even have the desirable effect of giving the image texture and facilitating depth perception by the pilot. In general, however, low speckle noise levels (small variability's) are desirable in the radar data.

In order to quantify small and large variability's, the parameter actually measured under this program was the signal-to-variability ratio. This ratio was obtained by dividing the signal level difference between the terrain and the runway by the weighted average variability for the terrain and runway.

The image quality metrics defined above were computed for the data provided by the Honeywell radar at two points in the systems. First, the raw data output provided by the radar receiver was analyzed. These data were obtained prior to the processing necessary for presenting these data to the HUD. The raw radar data were not recorded continuously, but a discrete image corresponding to a complete azimuth scan of the radar was captured roughly every four seconds during approach and roll-out. Each of these discrete raw radar data images is called a snapshot. The image quality analyses of these snapshots were performed by GTRI and are described in this report (Section 3.4.8).

Second, the same image quality metrics were computed for the RS-170 video presentation of the radar data, just prior to display on the HUD. These video images were presented in

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Second, the same image quality metrics were computed for the RS-170 video presentation of the radar data, just prior to display on the HUD. These video images were presented in

As indicated earlier in this report, surface reflectivity (and RCS), volumetric reflectivity, and atmospheric attenuation are all fundamental phenomenological parameters. The accurate measurement of these parameters requires that the radar be fully calibrated so that absolute received power levels are known. This calibration process typically requires that a standard radar reflector of known RCS be placed in the scene so that measured power levels can be associated with specific RCS values. Typically, two or more such standard reflectors are used to improve the accuracy of the calibration process.

These four "calibrated" parameters define the basic phenomenology that determines how well the radar can image the airport scene of interest. However, for any given approach, they are not essential for quantifying the observed sensor performance. The observed contrast, sharpness, etc. ***define*** that performance. Nonetheless, the phenomenological parameters help ***explain the*** observed performance.

Not only are these parameters important in explaining sensor performance in a given scenario, they also are critical -to extrapolation of the observed performance in one scenario to some other, different scenario. The contrast observable between a concrete runway and surrounding grass can be predicted based on the measured contrast for asphalt runway surrounded by grass, and knowledge of the respective reflectivities of concrete and asphalt. Thus; even though they require the extra step of fully calibrating the radar scene, these parameters were measured under the SVSTD program because of their importance for sensor performance assessment.

3.4.7.2. Summary of Radar Performance In Flight Tests

Measured contrast in clear weather was high, permitting the pilot to declare detection of the airport at a mean range of 1.5 nm, with a standard deviation of 0.26 nm. These detection ranges corresponded to measured contrast values between roughly -0.6 and -0.8.

The values of contrast measured during fog events were generally as high or higher than those measured during clear weather. Fog particles are too small to provide excessive attenuation of millimeter waves at the ranges important for these tests. The wetting action of the fog may also tend to enhance the backscatter from the surrounding terrain and thus increase the measured contrast. The test pilots were able to successfully detect the runway even in very dense fogs characterized by zero visibility or zero ceiling. Good contrast was observed in the measured data for heavy fogs characterized by 1/8 nm optical visibility's and vertical penetrations less than 100 feet.

The specific effects of rain on the available contrast are not well-understood. An attempt was made to extrapolate from clear-weather contrast measurements with the aid of the particle size distributions measured in flight. The in-flight drop-size measurements, and the calculation of estimated attenuations and rain rates from them, permitted estimates to be made of the reduction in signal levels due to the presence of this precipitation. These calculations indicate poor contrast at a 10 mm/hr rain rate and almost no contrast at a 29 mm/hr rain rate for the specific drop-size distributions measured. Results from the tower test indicate poor contrast at a 12.9 mm/hr rain rate but fairly good contrasts at 1.2 mm/hr and 5.3 mm/hr rain rates. Clearly, contrast tends to decrease with increasing rain rate. Contrast is also expected to be a function of the specific drop-size distributions encountered. Additional data are needed to better understand these relationships.

Accumulated snow was observed to greatly diminish the available contrast. When snow is present on both the runway and the terrain, this lowered contrast is due to homogenization of the scene by the roughly uniform snow layer. Plowing the runway enhanced the measured contrast by lowering the backscatter from the runway but improvement was not sufficient to produce a usable image. Falling snow, as opposed to accumulated snow, should not degrade the scene contrast significantly unless the snow is quite heavy. These conclusions for snow are preliminary since they are based on a small number of available snow scenes, for which quantitative physical data characterizing the snow (free water content, etc.) are not available.

The analyses described above indicate that of the three image quality metrics, contrast is the most important in predicting when the runway can be recognized in the image. The sharpness metric was difficult to accurately quantify based on the measurement technique employed. Measured sharpness values were typically about 1 to 5 pixels but varied in an apparently random fashion within this range as a function of distance to region of interest. There were also no clear trends in measured sharpness as a function of weather conditions.

Signal-to-variability results were somewhat more consistent. For slant ranges of about 1500 meters or less, the measured SVR values for clear weather, fog, and snow were typically greater than five. For slant ranges greater than 1500 meters or so, the SVR typically fell in the range of 2 to 8. A SVR of 5 indicates that the signal the pilot is trying to detect (namely, the transition between the runway pavement and the surrounding terrain) is five times larger than the background variability from which this signal must be extracted.

The SVR values measured indicate that in general for clear weather, fog, and snow, the signal to be detected is significantly larger than the background variability in the scene. These relatively large SVR values lend insight into the runway detection process that faces a human. Namely, this process is best viewed as acquiring a signal (runway-terrain transition) which has grown large enough to cross some detection threshold, rather than as a process whereby the signal (transition) must be extracted over time from a highly variable background which tends to mask the desired signal.

In this view, detection of the runway is largely determined by the absolute signal itself, rather than the signal compared to the background variability. And the most direct measurement of this signal alone is contrast. Thus, the relatively large signal-to-variability ratios tend to reinforce the importance of contrast in runway detection.

There is also considerable evidence supporting the importance of contrast. Throughout the flight test program, contrast was found to correlate well with the subjective image quality perceived by the pilot as well as by the radar analyst. In general, the measured contrast fell between -0.6 and -0.8 when initial detection of the runway was reported by the pilot in clear weather. Thus, the contrast at pilot detection was fairly consistent.

3.4.8. Image Quality Performance

During each approach, the pilot was instructed to give a verbal callout when he could confirm that the runway image had been identified. Using the time of those callouts, the image quality was examined to determine if metrics commonly used in other imaging applications correlated to the detection of airport features in the MMW raster images.

It was planned that this work would be done using a through-the-HUD video camera, permitting the analyst to use the same scene used by the pilot. When the through-the-HUD camera capability was not achieved with sufficient quality in time to support image analyses, a secondary approach using the recorded sensor video output was used. This video output does not reflect the settings of the HUD raster brightness and contrast controls, nor does it suffer degradation from the outside scene brightness . However, since the pilots used a repetitive technique in adjusting the HUD controls, it was felt that the metrics would reflect a relatively constant difference between the measured values and those actually seen by the pilots.

The digitized image used for the analysis was made up of 480 horizontal image scan lines, each of which could have 640 pixels or dots of varying brightness along its length. Actual images from the sensors often did not incorporate all of these lines or pixels, averaging 463 image scan lines and 63 1 pixels per scan line. The convention for locating a point number (479) at the bottom of the image was to count pixels as 0 on the left and increasing to a maximum of 639 at the right edge. The digitized scene covers a full 30 Hz field of the interlaced video. The field is made up of two separate 60 Hz frames which are offset by one image scan line. Since the imaging sensors produce their video data at the frame rate (1/60 second), the interlacing causes the two adjoining even/odd scan lines to have the same or very close data values. This accounts for the characteristic pairing of data points seen in the plotted contrast data for adjacent even/odd image scan lines.

Contrast

Based on the GTRI work with raw radar data, the contrast between the runway and the surrounding terrain appeared to have the most promise as a correlation factor. This analysis of image quality is consistent with the GTRI analyses of raw radar data in the formulation of contrast. Zero implies no contrast; larger negative numbers imply increasing contrast with the runway darker than the surrounding terrain; and larger positive numbers imply increasing contrast with the runway brighter than the surrounding terrain.

The data plots used for the analysis provide the “runway to terrain” contrast for each video scan line of the image which passed through the runway. The image counts scan lines from the top to the bottom, so scan lines with smaller numbers represent the far end of the runway and scan lines with larger numbers represent the near or approach end of the runway.

Figures 28 through 3 1 show the typical evolution of the runway scene during the approach.

- Figure 28 presents the runway-to-terrain contrast at 2.5 Km from touchdown. Notice that contrast increases fairly linearly from the far end of the runway to about mid-field (scan lines 121 - 135) and then becomes a relatively constant value (about -0.75) for the near end of the runway (scan lines 136-152).
- Figure 29 presents the runway-to-terrain contrast for the runway at the point at which the pilot identified the runway image.
- Figure 30 presents the runway-to-terrain contrast for the same runway when the aircraft is approximately 200' above the airport's surface and nominally 1.2 km from the touchdown zone. The constant contrast continues to be seen, the deviations are due primarily to interference of other objects such as intersecting taxiways or reflective objects along the runway.
- Figure 3 1 again presents the runway-to-terrain contrast for the same runway, but now at a point 50' above the threshold area. The decreasing contrast as the near end of the runway is partially due to the build up of "blockiness" in the radar's near field view. The effects of intersections and/or reflecting items are even more pronounced.

The correllation of contrast with the range from the runway at which the pilot declared a runway image was accomplished for 25 approaches covering much of the weather experienced by the SVSTD/SIED flight test and representative airports and terrain features.

The results are summarized in Table 13. Note that there are two columns for contrast: one labeled ***Average*** and the other ***Best,*** representing two ways of looking at the runway data.

- Average Contrast is the average over all of the scan lines going through the runway (i.e., all of those shown on the plot).
- Best Contrast assumes that the pilot only needs a few vertically aligned pixels to recognize the edges of the runway, and thus considers only the best contiguous scan lines (usually 4 or more) for averaging.

With the common band of recognition extending from -0.2 to -0.6 contrast, the data reflects more dispersion and slightly lower values than was seen in the contrast data taken at the radar sensor output. The most probable cause is in the processing of the radar data for presentation to the pilot on the video display. Some of the dispersion may be due to the use of runway contrast without a means to include other objects which aid in pattern recognition. Primary among these are the distinct and repeatable patterns created by runways, taxiways and parking areas as well as by reflectors in the scene such as light bars, runway arresting wires, VASI installations, and structures near the runway. A secondary aid to recognition may have been repeatable patterns in the ground terrain returns just prior to reaching runway recognition point. These usually include roads, fences, and other cultural features.

3.4.8.2. Variability And Sharpness

Variability and sharpness were considered as possible metrics for image recognition. However, analysis of variability and of sharpness in the video data was not done when the GTRI studies showed that they had a very low correlation in the raw radar data which form the video data.

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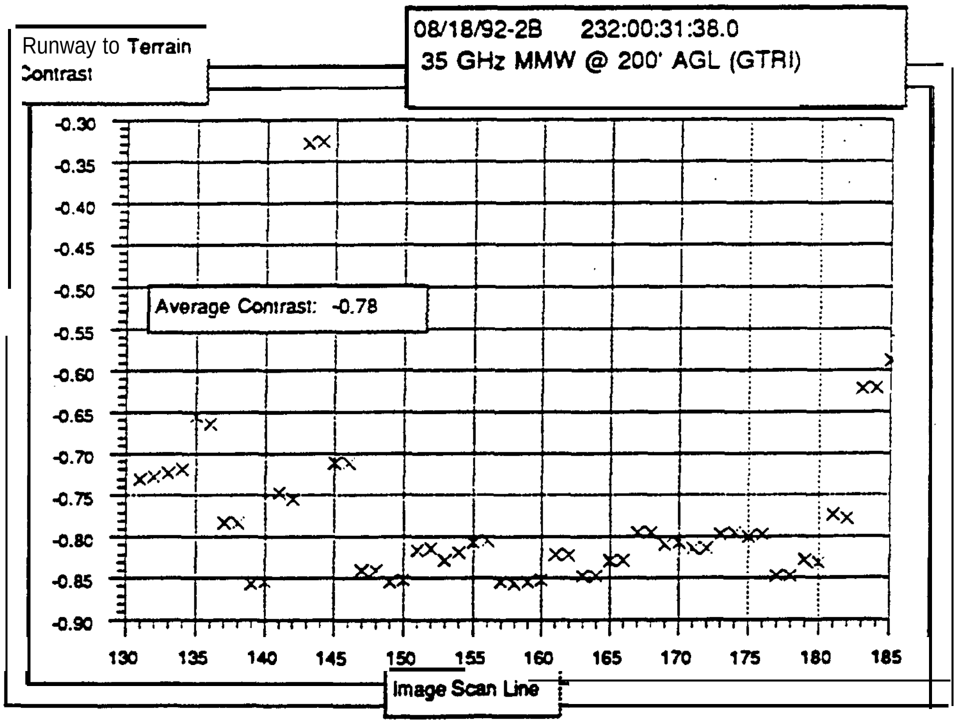

Figure 31. RS 170 Video Contrast - August 18, 1992-2B (NTD at 200 ft AGL)

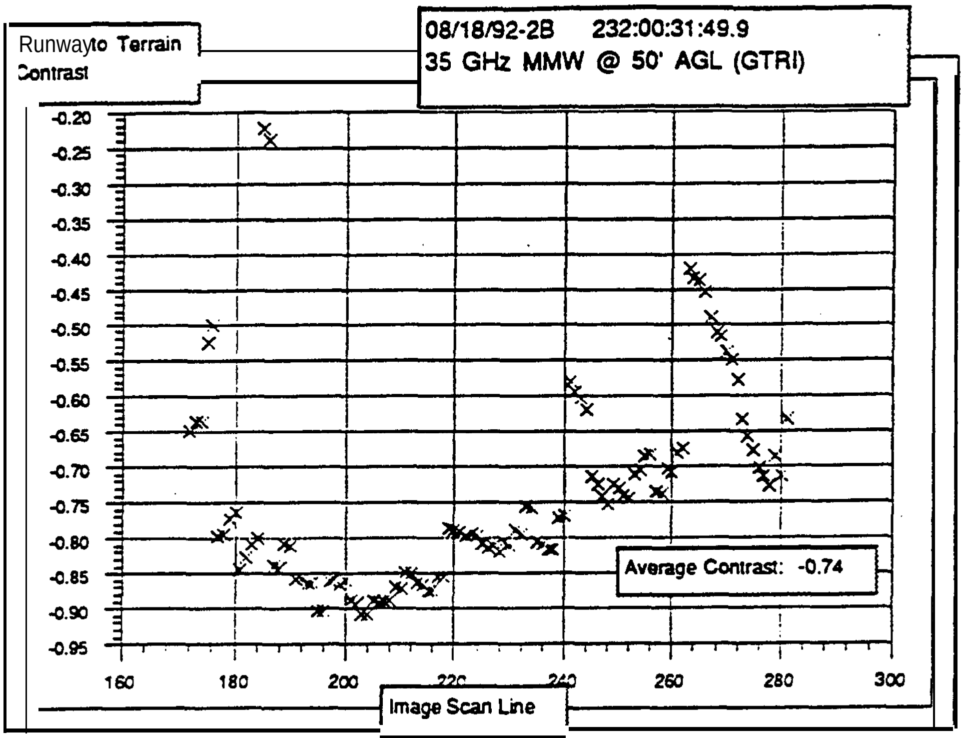

Figure 32. RS 170 Video Contrast - August 18, 1992-2B (NTD at 50 ft AGL)

Table 13. Summary of Contrast Metric Correlation to Runway Detection

PILOT CON-FIRMS RUNWAY CONTRAST METRIC CORRELATION					
Figure Number	Airport	Flight ID	Contrast Average	Contrast Best	Weather
4	NTD	08/18/92-2B	-0.56	-0.59	VMC
5	NTD	08/18/92-2C	-0.59	-0.75	VMC
6	NTD	08/18/92-2D	-0.50	-0.55	VMC
7	NTD	08/18/92-2E	-0.36	-0.44	VMC
8	NTD	08/18/92-2F	-0.51	-0.52	VMC
9	ACV	08/28/92-1A	-0.24	-0.27	W 0 X 1/8 Fog
10	ACV	08/28/92-1B	-0.40	-0.45	W 0 X 1/8 Fog
11	ACV	08/28/92-1C	-0.39	-0.50	W 0 X 1/8 Fog
12	ACV	08/28/92-1D	-0.24	-0.24	W 0 X 1/8 Fog
13	ACV	08/28/92-1E	-0.25	-0.48	W 0 X 1/8 Fog
14	ACV	08/28/92-1F	-0.42	-0.45	W 0 X 1/8 Fog
15	ACV	08/28/92-1G	-0.37	-0.37	W 1 X 3/8 Fog
16	ACV	08/28/92-1H	-0.40	-0.50	W 1 X 3/8 Fog
17	LFI	09/25/92-1B	-0.43	-0.50	6 SCT M9 BKN 12 OVC, 1 1/2 L-F
18	LFI	09/27/92-1D	-0.31	-0.35	VMC
19	NHK	09/25/92-1D	-0.23	-0.36	-X 3 SCT M7 BKN 10 OVC, 2 R-F
20	NHK	09/27/92-1C	-0.27	-0.38	VMC
21	MIV	09/25/92-1E	+0.24	-0.32	M5 BKN 10 OVC, 2 R-F
22	MIV	09/27/92-1B	-0.49	-0.50	VMC
23	ACY	09/25/92-1I	-0.18	-0.33	M5 BKN 12 OVC, 2 R-F
24	ACY	09/27/92-1A	-0.29	-0.37	VMC
25	ORH	09/26/92-2A	-0.32	-0.41	W 1 X, 1/4 L-F
26	ORH	09/26/92-2B	-0.37	-0.42	W 1 X, 1/4 L-F
27	ORH	09/26/92-2C	-0.37	-0.49	W 1 X, 1/4 L-F
28	HTS	09/28/92-1B	-0.51	-0.57	-X, 1/16 Fog
Average Values:			-0.34	-0.44	
Standard Deviation:			0.16	0.11	

3.4.9. Pilot/System Performance

The performance of the experimental Synthetic Vision System and of the pilots in using it is reported in the form of aircraft trajectory and attitude states, and the subjective opinions of the pilots who used it. These data reflect the ability of the pilots to interpret and use several sources of information including, 1) the image provided by the SVS sensor, 2) the flight guidance cue, and 3) the HUD symbology.

The image provided on the HUD was used by the pilots as the primary source of information upon which to base the decision to go below Cat I minimums on Type I ILS guidance. The "runway-image" call made by the evaluation pilot was highly significant because it indicated that he had an image of the landing runway that was sufficiently good to continue below Cat I minimums, on a Type 1 beam, with no transmissometers (RVR data), and no touchdown zone or centerline lights. The altitude and range at which the pilot called "runway image" is an important measure of sensor and system performance. The safety pilot was required to execute a missed-approach if he did not hear the "runway image" call before reaching the published decision-height for approaches in actual Cat II or Cat IIIa conditions. Pilot commentary indicated that pattern recognition of the runway(s) and taxiway(s) played an important role in the pilot decision to call "runway image".

The reported results are confined to the flight tests in which the Honeywell 35 GHz MMW radar sensor was used as the source of the HUD raster image. Suitability tests with the 94 GHz sensor indicated a substantial range limitation. The reasons for this limitation are not understood but are believed to be associated with the radome, the limited power of the transmitter and limitations in the processing of the radar data. Because the runway image call altitude was consistently below 200 feet (Cat I decision-height), a decision was made not to conduct formal testing with the Lear 94 GHz MMW radar. Data obtained during suitability testing indicated that the average runway image call altitude was 168 feet (standard deviation 26 feet) and the range was 0.50 nm (standard deviation .08 nm). Another shortcoming of the 94 GHz MMW was substantial noise in the foreground at altitudes below 100 feet above the runway. This noise interfered with the pilot's ability to see the stroke symbology including the flight director. There were indications that the resolution of the 94 GHz sensor would be quite good in the absence of the above problems.

The Kodak 3 - 5 micron forward looking infrared (FLIR) sensor provided excellent image quality in conditions without measurable moisture. The performance of the FLIR sensor deteriorated in conditions of measurable moisture to the point that it did not provide a useful image. This was determined early in the program when the FLIR sensor was used as the primary sensor on alternating approaches in actual Cat II and Cat IIIa conditions. After consistent results in actual Cat II and Cat IIIa conditions indicated the FLIR sensor did not produce a usable image at the Cat I decision height (resulting in a missed approach), it was decided to abandon those approaches remaining in the test matrix using that sensor. However, in all actual weather, the FLIR image was monitored by the test engineer, and recorded on High-8 video tape. Any instances in which it appeared that the FLIR might provide a usable image were followed by an approach with the pilot using the FLIR image on the HUD. The results were invariably consistent; the FLIR sensor did not provide a useful image in measurable moisture.

3.4.9.1. Experimental System (35 GHz MMW Sensor) Performance in Terms of Range and Altitude Where Pilot Called Runway Image*

3.4.9.1.1. Variation Between and Within Pilots.

The variability of the runway image call between pilots and the repeatability of the call for each pilot are significant because they are measures of the confidence the pilots had in identifying the airport pattern (taxiways, runways, etc.) and the landing runway. A large variability would indicate that the call is highly subjective, and would be indicative of a low level of confidence. The average range for the runway image call was 1.5 nm in clear air and 1.2 nm in fog. The average altitude above the runway for the call was 500 feet in clear air and 385 feet in fog. The standard deviation was approximately 1/4 nm in range and 100 feet in altitude, both in fog and in clear air. These trends were reasonably consistent across all three of the evaluation pilots. Pilot commentary indicated that the runway image call was made only after it was possible to identify the landing runway with a high level of certainty. They also noted that the image tended to "pop into the field-of-view" suddenly and with reasonable quality as opposed to a more gradual improvement from poor to good image quality. This may explain why the image call ranges and altitudes were quite repeatable with each pilot, and were consistent between pilots.

3.4.9.1.2. Effect of Fog On Runway Image Call

The effect of fog compared to clear air on the range and altitude for the runway image call was not operationally significant. In fact, the pilots were not aware that there was a measurable degradation until the data were plotted. It will be noted that this slight degradation on the range of the runway image call is not consistent with the slight improvement in contrast at the point of runway identification found in the analysis of the radar sensor flight test

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[2] The range for the runway image call was defined as the range from the aircraft to the runway threshold. The call was assumed to occur the instant that the pilot initiated the call.

performance. While further analysis is needed of the data from the tower sensor studies, from the sensor performance studies performed as a part of the flight tests, and from the pilot performance studies to fully understand the differences found in them regarding effects of fog on SVS performance, the conclusion is clearly that the effect of fog on the radar sensor performance was negligible.

3.4.9.1.3. Effect of Rain On Runway Image Call

Increasing rain-rate significantly reduced the range at which the pilot called runway image. The data points at zero rain-rate were taken on dry runways.

The effect of rain on image quality is complex due to the variability of the rain activity as the aircraft approaches the runway (rain-rate tends to be a function of time and position). While the details are not well understood, the important finding is that moderate rain had a definite adverse effect on the image. The use of radar reflectors to improve the image quality in moderate and heavy rain should be studied as a means to overcome this deficiency.

It is notable that in all conditions where the rain-rate was high enough to degrade the radar image, the visibility reported by the tower and the runway visibility reported by the pilot were well above Cat I minimums. This experimental finding should be expanded by investigating statistics on visibility as a function of rain-rate and drop size distribution. If the visibility is only reduced to below Cat I minimums in very heavy rain, it could be argued that there is not a critical need for SVS in such conditions. Additionally, very heavy rain tends to occur in short intervals so that it may be possible to circumvent the problem by delaying the approach during the low-probability short-duration heavy-rain events.

3.4.9.1.4 Effect of Snow On Runway Image Call

Four approaches were made to Pueblo Colorado (PUB) with light-to-moderate snow falling This was officially reported as light snow, but the tower noted that it was moderate on some approaches . There was approximately 1 to 2 inches of very wet snow (almost slush) on the runway and surrounding areas. The tower reported visibility was 3/4 miles in fog and visual acquisition of the runway occurred at about 300 feet above the surface for most approaches. Two evaluation pilots each flew two approaches. Both pilots reported that there was never a usable runway image on the HUD. One of the pilots noted that the approach light stands provided a good radar signature at a range of about 1.2 M-I. The ability to see the approach lights before the runway provides some evidence that radar reflectors may be effective as a means to overcome the inability of the MMW radar to image the runway surface in these conditions.

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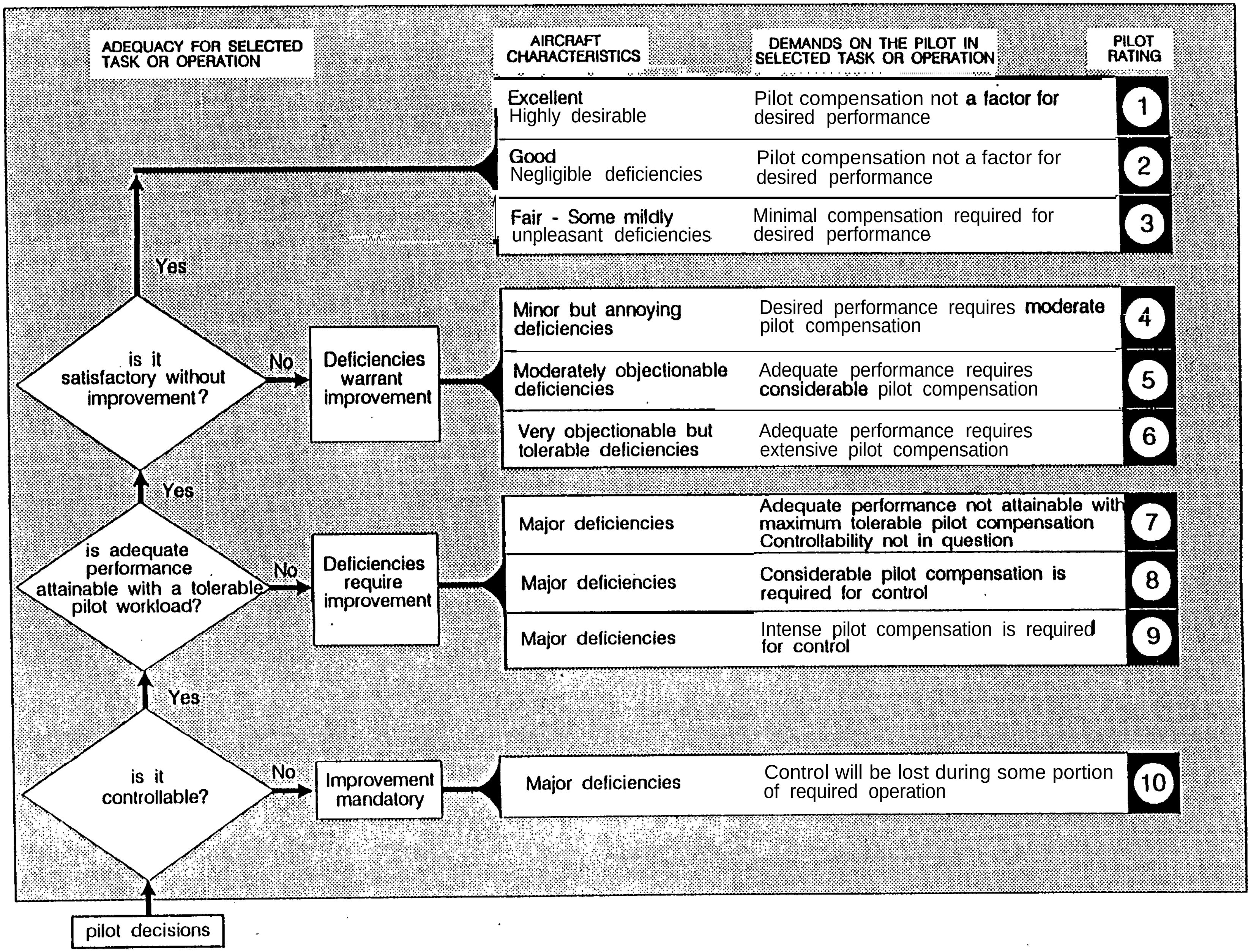


Figure 33. Cooper Harper Handling Qualities Rating (HQR) Scale

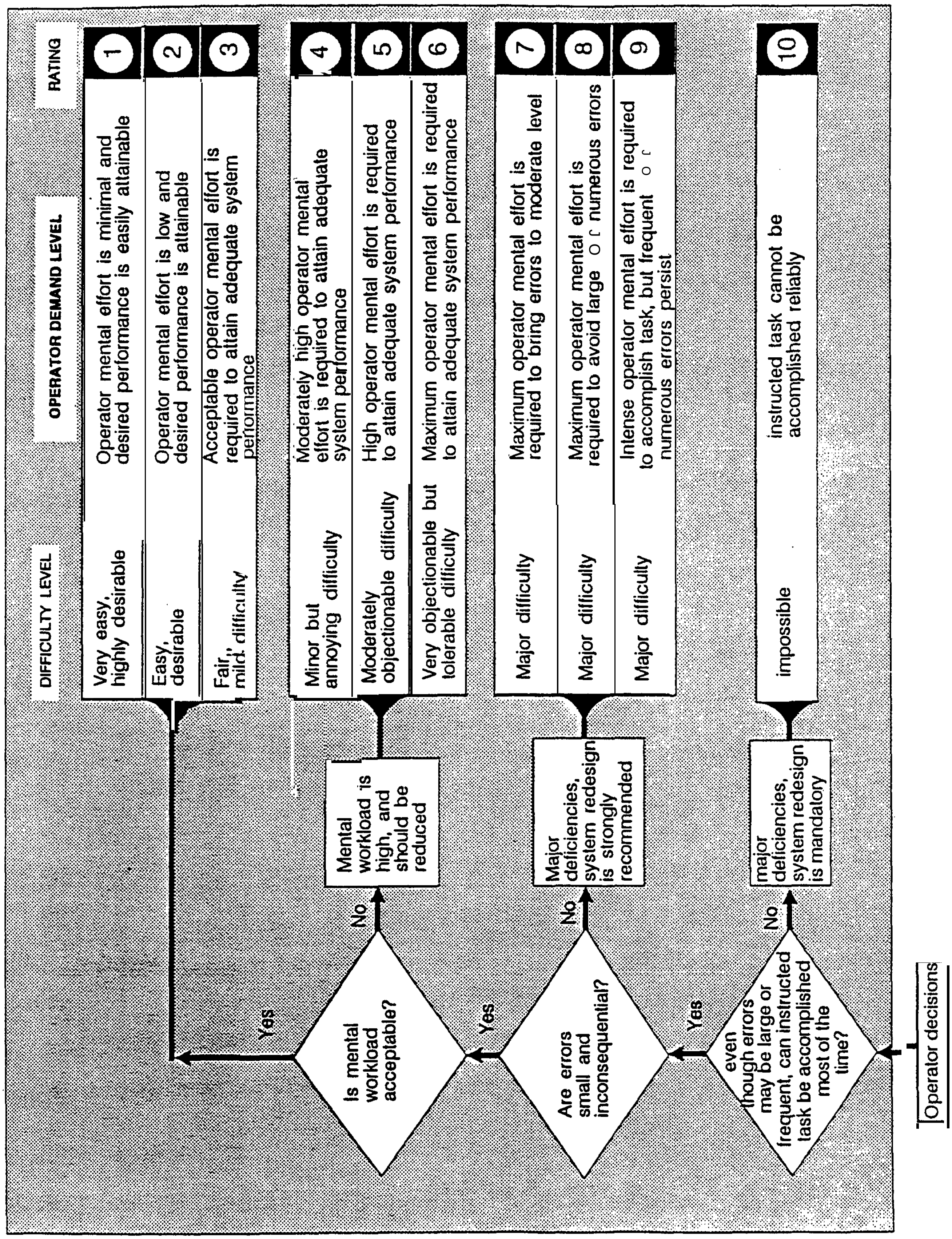


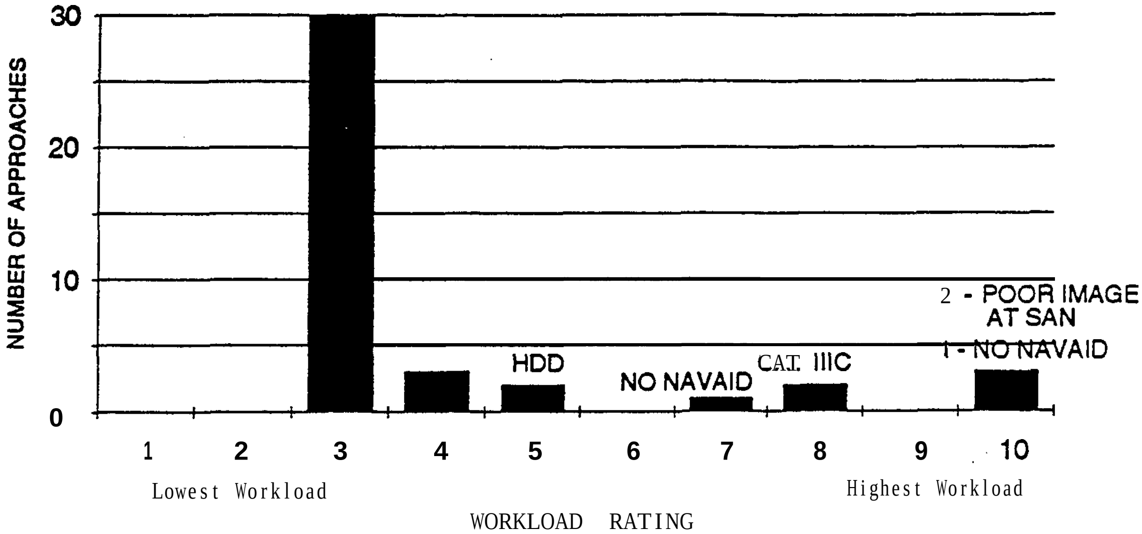
Figure 34. Modified Cooper Harper Workload Rating Scale (MCH)

Table 14 Performance Standards

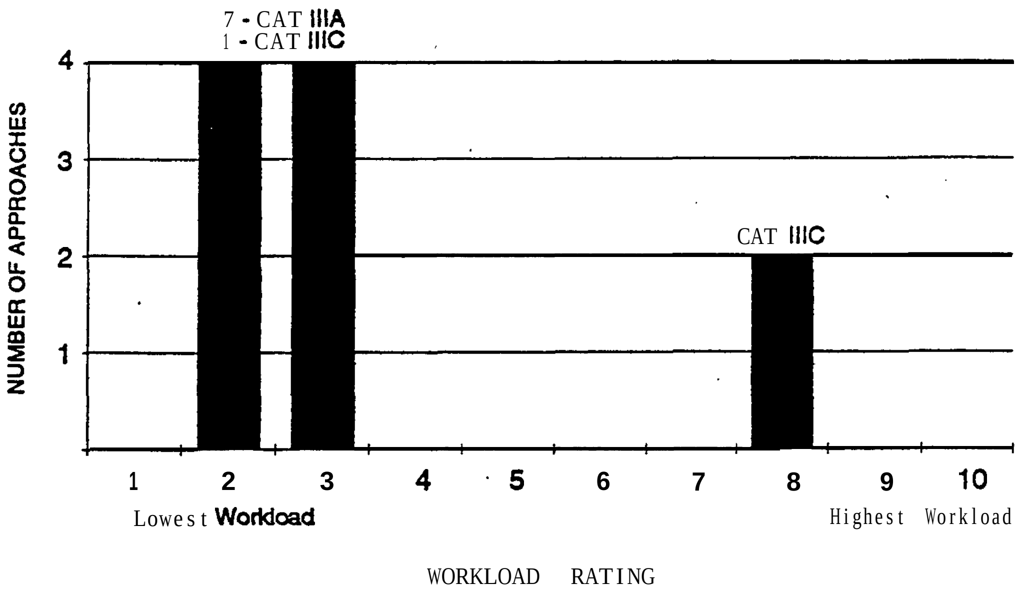
	Desired Performance	Adequate Performance
Glideslope and localizer tracking above 200 ft. AGL.	± 1 dot	± 2 dot
Glideslope and localizer tracking between 200 and 50 ft AGL.	± 0.50 dots	± 1 dot
Airspeed control with respect to target speed.	± 5 knots	+ 10 knots - 5 knots
Flare performance	Touchdown between 1000 and 2000 feet of the runway threshold. Touchdown within 10 feet of centerline Sink rate subjectively smooth-to-firm	touchdown at greater than 500 feet and less than 3000 feet of the runway threshold. Touchdown on runway with at least 5 feet of margin from edge. Sink rate subjectively hard.
Takeoff roll	Maintain track within ± 10 feet of runway centerline. Achieve target climb attitude and speed with little or no bobbling or lateral directional problems.	Maintain aircraft on runway with at least 5 feet of margin from edge. Maintain positive control of pitch attitude and climb speed. No safety pilot takeover necessary.
Landing roll	Maintain track within ± 10 feet of runway centerline.	Maintain aircraft on runway with at least 5 feet of margin from edge

3.4.10.1. Pilot Rating of Workload In Simulated Cat IIIa and Cat IIIc Conditions

The frequency distributions of the subjective workload ratings for approaches and landing flares to simulated Cat IIIa and Cat IIIc conditions are shown in Figure 35. This data indicates that the majority of the ratings were 3 (ie., satisfactory without improvement). This should not be construed to imply that the experimental SVS was acceptable as a certified system, but rather that it was acceptable for specific approaches under the specified test conditions; in this case simulated IMC. IMC was simulated by placing a cardboard shield in front of the HUD, and removing the shield at the appropriate time, e.g., 50 feet for simulated Cat IIIa. The cases rated as 4 or worse provide valuable insight into potential problems with an operational SVS and were investigated to the extent that resources permitted.

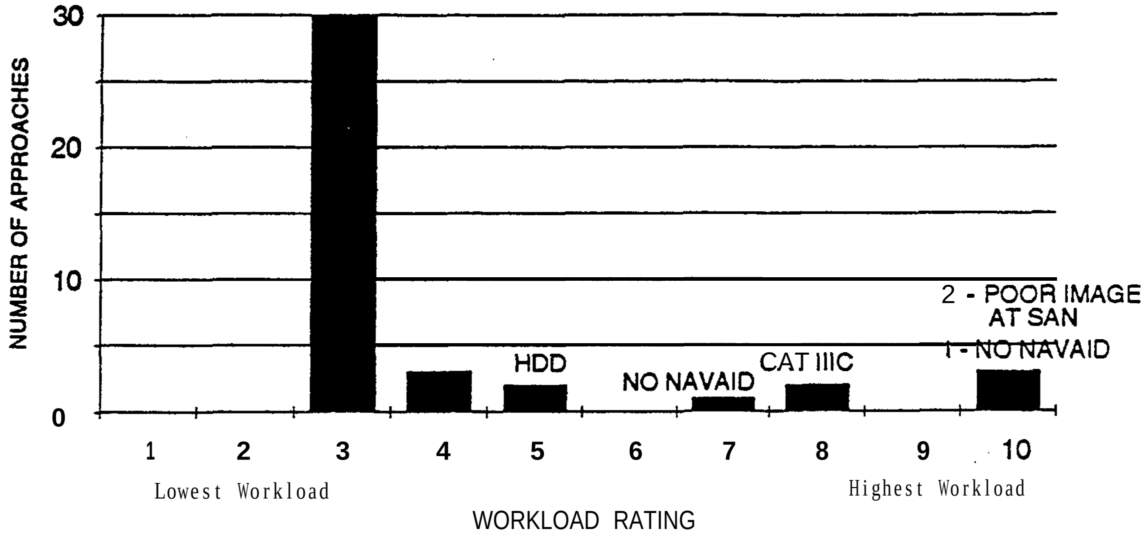


a) **Workload Ratings for Approach Segment From an Altitude of 250 ft to 50 ft**



b) Workload Ratings for Flare

Figure 35. Frequency Distribution of Pilot Workload Rating Data for Simulated CAT IIIa and CAT IIIc Approaches



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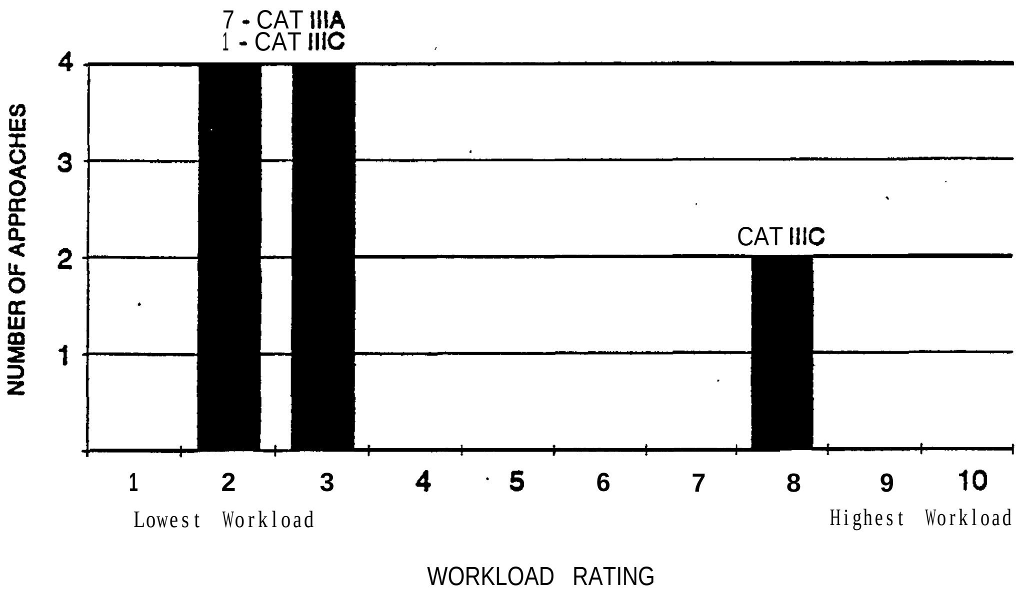

b) Workload Ratings for Flare

Figure 35. Frequency Distribution of Pilot Workload Rating Data for Simulated CAT IIIa and CAT IIIc Approaches

3.4.10.3 Summary Comments Regarding Pilot Performance and Workload Ratings

All approaches made in actual or simulated Cat II or Cat IIIa conditions were acceptable at airports with long runways (e.g., Pt Mugu (NTD) and Vandenberg (VBG)). For approaches to shorter runways (6000 feet or less), issues such as beam bends, image quality, crosswinds, tailwinds, and pilot training became significant (e.g., Arcata (ACV) and Santa Maria (SMX)). The workload associated with short runways tends to be less severe if the runway image is available well above the decision height. The ratings of 10 all occur for cases where the runway image call occurred below 300 feet, and less than 1 nm from the threshold. This would indicate that better MMW range is more important for short runways where the margin for error is less. An early runway image call gives the pilot more time to incorporate the image into his instrument scan and control strategy, so that beam anomalies and crosswinds are more easily handled. For example, the problems encountered at ACV resulted in workload ratings of 4, and the runway image call was made at about 500 feet. The only other rating worse than 3 (workload rating = 4) was assigned at Carlsbad/Palomar CA (CRQ), which is only 4700 feet long, and the runway image call was made at 490 feet. The approach speeds (135 to 150 knots depending on weight) and handling characteristics of the G-II are similar to transport aircraft so that these results are directly applicable to that class of aircraft.

The flare and landing data are summarized in Figures 34b and 35b. They indicate that there were no significant problems with that task for Cat II and Cat IIIa. The pilots all indicated that the flare cue on the HUD provided adequate guidance. The exception was for the simulated Cat IIIc (O/O) landings where the workload was judged to be very high by two of the three pilots. The flare cue used for this experimental system was not optimized to provide a landing footprint that would insure high probability safe landings on marginally short runways, and in varying wind and wind-shear conditions. It would be important to optimize the flare cue for a commercial system.

3.4.11. Summary of Pilot Commentary.

A summary of the evaluation pilots' commentary related to strengths and shortcomings of the experimental SVS is presented below.

General Comments Related to Synthetic Vision System performance

- All of the evaluation pilots felt that the system was viable as a means to achieve Cat IIIa minimums on Type I ILS guidance, and to achieve lower minimum descent altitudes on non-precision approaches.

- All of the evaluation pilots were enthusiastic about the use of a head-up display to assist in the transition from use of the image to use of outside visual cues.

Comments Related to the 35 GHz MMW Radar and FLIR

- The FLIR image was excellent, or it was nonexistent. Excellent images were observed in conditions of haze or at the bottoms of cloud bases. All pilots demonstrated Cat IIIc (O/O) landings using the FLIR image in simulated IMC conditions with workload ratings of 3 or better. When there was visible moisture (dense fog or rain) the FLIR did not produce a usable image.

- The MMW radar image was usable to identify the airport and the landing runway. The pilots commented that they relied heavily on airport runway/taxiway pattern recognition to insure that they did not mis-identify the runway as a road or other object.

- The pilots were able to learn radar signatures of the terrain approaching airports. For example certain roads, fields, and towns showed up very well on the radar. It was important to learn that some objects produce a radar return out of proportion to what that object produces in the normal visual field. For example the radar return of a chain-link fence along the side of the runway or arresting cables across the runway a Pt. Mugu were very bright. The radar return of approach light stands was very bright and was often seen well before the runway image (e.g. Worcester MA (ORH) in rain and fog, and Pueblo CO (COS) in snow conditions).

- The image was excessively sensitive to the aircraft pitch attitude. It was necessary to conduct all approaches with full flaps to maintain the proper nominal pitch attitude of zero. In turbulence the necessary changes in pitch attitude to maintain glideslope caused the image to fade in and out. It also caused the raster brightness to vary significantly so that it was not possible to set the proper value. Pitch attitudes of greater than 2 degrees had a noticeable degrading effect on the image.

- The raster brightness that was best for the approach, was too bright after breakout. In Cat II and Cat IIIa conditions, breakout consists of a dim view of the runway at best. The edges of the runway were obscured by the green raster because the radar image was not perfectly aligned with the runway and/or the radar image was more narrow than the runway. Some pilots compromised by using a less than desirable brightness on the approach, and others had the Test Director turn off the raster at breakout. One solution would be to install a "kill switch" on the column, but this could be a problem if the pilot encounters a fog bank on the runway.

- The latency in the image was too large, and was estimated to be approximately 200 ms. for gentle attitude changes and 400 ms. for large angular rates. It was particularly noticeable in roll.

- The radar image sometimes "jumped", especially at low altitudes. It is suspected that this is a result of the altitude data used as input to the B-to-C scope conversion. The altitude signal consisted of pure barometric data above 1000 feet and blended to pure radar data at touchdown. Significant variations in the terrain at low altitude would result in a discontinuity in the B-to-C conversion process.

- There was a tendency to get very low on short final when using the flight path symbology and MMW image to construct a 3 degree glideslope. This is believed to be a result of mis-registration of the radar image with the outside world. There is also reason to believe that the flight path symbology does not provide sufficiently compelling glideslope error data to the pilot at altitude below 200 feet.

Comments Related to the Head-Up Display Hardware and Symbology

- The pilot's head must be in a certain position to properly view the HUD, called the eyebox. For some pilots, it was necessary to make compromises to get into this position. For example, pilot LO could not use the toe-brakes. All of the pilots had to sit too low for an optimum view over the glareshield. It is well known that a high seat position is best when making approaches to very low minimums.
- Some type of auto brightness control is required for the raster.
- The flight director symbol was off the display in large (about 25 knot) crosswinds. The flight director should never leave the display, even at the expense of conformality with the outside world.

3.5. LESSONS LEARNED.

Early in the formulation of the SVS Technology Demonstration, a survey was performed of the status of the technologies needed to demonstrate the SVS concept and the key issues were identified that would have to be resolved in the course of successfully implementing the SVS concept as an operational capability. As the Technology Demonstration program progressed, these issues began to be thought of in terms of operational, systems and technology issues with a great deal of overlap between these three general categories of issues. Summarized briefly below are the more significant lessons learned in the flight test phase of the SVS Technology Demonstration.

1. The quality of the image produced by the experimental 35 GHz radar system was sufficient to support approaches and landings in Cat IIIa conditions on Type I ILS guidance. A majority of the approaches were flown using ILS approach procedures and guidance. Terrain imagery cues were verified on the display early in the approach (typically 1200-1500 ft AGL). At about 450-550 ft. AGL a runway image could be seen on the display of sufficient quality to use as a reference for flight path control. At 200 ft. AGL, the flight test minimums required the presence of a good raster image to continue the approach. At 50 ft AGL a vision-obstructing cardboard shield was manually removed, if previously put up, to permit the evaluation pilot to transition to outside references. The flare and landing rollout were flown visually for most of the approaches. Other than in conditions of moderate to heavy rain or snow covered terrain, runway and adjacent taxiway image quality were good with lateral, near, and far runway and taxiway edges relatively well defined.

2. Performance of the 35 GHz system in fog was excellent, providing good images in the presence of all advection or radiation fog in which flight tests were conducted right down to zero ceiling and visibility conditions.

3. Performance of the 35 GHz system in light rain (less than 6-8 mm per hour) was adequate. In moderate (8-10 mm per hour) to heavy (22-26mm per hour) rain, image degradation consisted of a pronounced reduction in maximum range. The existence of pooled water on and beside the runway coupled with heavy rain further reduced the usefulness of the image. In all rain conditions encountered, however, runway visibility always exceeded that required for existing ILS minimums.

4. Performance of the 35 GHz system through falling snow was excellent. In the very few snow conditions available during the test period, however, snow cover of the terrain surrounding the runway dramatically reduced the range at which a useful image could be attained. Although the runway approach lights could be clearly seen in the images on all approaches, contrast between the runway surface and surrounding terrain was nonexistent until very low (below 200 ft.) on the approaches. These effects were apparently the same whether or not the runway surface was plowed and even in the presence of piled snow along the runway edges.

MMW sensor range is key to the identification of the airport runway prior to reaching the decision height (DH) or minimum decent altitude (MDA)/visual descent point (VDP) in an IMC approach where visual identification is normally required to continue the approach. The synthetic vision system must provide a synthetic visual image of sufficient quality prior to that point in the approach to permit the decision to be made to continue with the approach using the sensor image. Unlike today's instrument approach in which the per- formance of the human eye and brain permit an almost instantaneous decision upon reaching the DH or MDA/VDP, the poorer resolution and hence fewer cues in the SVS image will require a greater period of time for the pilot to assimilate the needed in-formation and make the decision.The experimental system 35 GHz radar range was adequate for Type I ILS guidance.

6. A requirement for image enhancement is highly dependent on the intended operational use of the SVS system. Surprisingly, system resolution was not the limiting factor for runway detection and identification or for accomplishing the approach to the initiation of the flare maneuver. On the other hand, the somewhat coarse resolution of the 35 GHz system (approximately 0.8 degrees in azimuth and 12-15 meters in range), and the rather jagged runway and taxiway edges in the video display during the latter phases of the flare, landing rollout and taxi contributed to the very limited usefulness of the experimental system to the pilots for those operations. Although simulated (cardboard shield up) zero visibility landings were made, pilot comfort in lateral aircraft control in the flare and for taxi or rollout was degraded significantly by the lack of adequate runway edge definition and by the limited vertical field of view of the image when the aircraft was on the ground.

7. Antenna pitch stabilization is necessary to keep the antenna elevation pattern pointed at the runway surface as aircraft pitch attitudes vary during the approach and for ground operations. The usefulness of a runway radar image depends on consistency in the difference between radar energy forward scatter on the runway and taxiway surfaces (dark image areas) and back scatter from the runway surroundings (bright image areas). In the Technology Demonstration the antenna elevation angle of the 35 GHz radar system could be varied on the ground through adjustments inside the radome, but could not be varied in flight. Significant variations in image quality were observed on occasion with relatively small (1 to 2 degree) changes in pitch attitude on approach.

8. The specified maximum transport delay for the experimental system image of 200 milliseconds was exceeded in some circumstances with the 35 GHz sensor system by an approximate factor of two, reaching an estimated 400 milliseconds in periods of high roll rates. An image system latency of about 200 milliseconds did appear to be the value beyond which pilot workload and pilot acceptance rapidly degraded when the image was used as an element of the primary guidance system with the pilot in the loop. The transport delay experienced was largely a function of the limitations of the processing used in the experimental system.

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washout of surface terrain features and reduced operational usefulness. In dry moderate temperature conditions the performance permitted simulated (cardboard shield in place to block outside scene) zero visibility landings and supported good lateral control during rollout and taxi operations. No image was obtained during any of the fog, rain or snow conditions tested. Infrared sensor approaches were flown in day and night conditions, in temperatures from below freezing to above 100 degrees Fahrenheit, and in other weather conditions as specified for the MMW sensor using procedures identical to those used in testing the MMW sensor.

13. The HUD itself, even without runway imagery, reduced workload in the approach and landing.

14. HUD conformality and image registration are critical issues. The pilot depends on accurately registered image and symbology to provide cues for flight path control. The methodology must be developed and used in future SVS operations to ensure that hardware and software installation features provide the pilot a conformal, accurately registered image.

15. Increased brightness of the stroke and raster information displayed on the Head-Up Display is definitely needed in future systems. Improved control of the relative brightness of the stroke and raster information is needed. Also, control of the brightness of the raster image relative to the brightness of the outside scene is definitely needed when the outside scene appears during the approach. In the Technology Demonstration, high levels of cockpit ambient light sometimes caused the evaluation pilot to be unable to effectively see and use the raster image on the HUD. In some cases the stroke symbology was also difficult to see and use. To resolve the problem for the purposes of the flight test program, a sunshade was used over the windshield behind the HUD combiner glass. When in clouds the cockpit ambient light was much reduced and the pilot could view the HUD without the sunshade most of the time. Auto-brightness for stroke only was im-plemented in the HUD for the SVS flight test program and was only partially successful.

16. The flare control laws and display were adequate to ensure a smooth and safe touchdown virtually every time, and with minimal required training. Flare cues were adequate using the display and symbology cues alone (horizon, airspeed, radio altimeter height, flight director), in low visibility conditions. The flare cue consisted of a cross that filled the center of the circular flight director symbol, and flashed at about 1.5 Hz. Flashing of the flare cue began at about 50 ft. AGL during ILS approaches, and continued to touchdown. The flare cue did not, of course, compensate for lateral or vertical beam bends in the ILS guidance.

17. Coding the HUD symbology to annunciate when the display is no longer conformal is acceptable but the flight director should never be removed from the display. The HUD field of view (FOV) was 30 degrees laterally. During SVSTD approaches to landings

with high crosswinds (up to 35 knots at 90 degrees) the velocity vector became a dotted circle at the edge of the display, and the flight director vanished from the display.

18. HUD control laws were tailored for the flight tests using a fixed base engineering simulator at Douglas Aircraft Company. The ability to set the gains in the simulator and then fly them in the aircraft the same day was invaluable and undoubtedly saved much time in preparation for flight test.

19. There are as many different operational applications of SVS technology as there are users. Each operational scenario will have its unique functional requirements of the technology and will lead to variations in the systems derived to satisfy those requirements. At one end of the spectrum of applications of the SVS capability, and the most easily certificated and implemented, will be its use as an independent monitor of other components of approach and landing guidance systems. At the other end of the spectrum will be applications in which the pilot's cognitive skills will be incorporated as an integral part of the implementation of the SVS concept as a low visibility landing system. While likely to provide greater operational flexibility, this application will require greater certification effort because criteria for its certification do not presently exist. With sufficient development, SVS technology will substantially contribute to increased aircrew situation awareness and to the detection and avoidance of runway intrusions in all im-plementations.

4. CONCLUSIONS

Potential applications of Synthetic Vision System Technology are extensive and there appear to be no insurmountable obstacles to its implementation from an operational perspective. These applications promise dramatic improvements to the economics and safety of flight operations in low visibility conditions.

While this Technology Demonstration Program did not identify nor respond to any specific operational requirement, a carefully selected set of scenarios and associated flight test experiments were established in conjunction with the Program's Certification Issues Study Team to ensure that a reasonably complete cross section of potential users' interests were addressed. These operational scenarios included precision guidance approach and landing operations down to and through Category IIIc operations on Type I and Type II landing guidance systems, nonprecision approach and landing operations, no-navaid approach and landing operations, and airport surface operations including low visibility takeoff. While this joint government/industry SVS Program demonstrated the performance of ***existing*** technologies only and did not investigate any aspect of the costs of developing and implementing the SVS technologies, the Program's participants identified and investigated all technical and certification issues in sufficient depth to conclude that there are no insurmountable operational or technical or certification obstacles to implementation of the SVS capability.

It remains for potential users to establish carefully validated operational requirements for low visibility operations from which cost effective functional and system requirements can be established.

The SVS Technology Demonstration Program has caused the user industry, the manufacturing industry and the regulators to become aware of the potential of SVS technologies for substantial operational, economic and safety improvements. Substantial research is now required to establish adequate models of low visibility conditions and sensor phenomenology with which to examine alternative sensor technologies, to examine alternative system concepts with which to satisfy the user's operational requirements in the most cost effective manner, and to establish the relationship of SVS technology to other technologies such as GPS in meeting those operational requirements. Probably the most difficult challenge to industry is in performing the necessary economic studies with sufficient depth to fully understand the true costs and benefits of the many technology options.

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While this Technology Demonstration Program did not identify nor respond to any specific operational requirement, a carefully selected set of scenarios and associated flight test experiments were established in conjunction with the Program's Certification Issues Study Team to ensure that a reasonably complete cross section of potential users' interests were addressed. These operational scenarios included precision guidance approach and landing operations down to and through Category IIIc operations on Type I and Type II landing guidance systems, nonprecision approach and landing operations, no-navaid approach and landing operations, and airport surface operations including low visibility takeoff. While this joint government/industry SVS Program demonstrated the performance of ***existing*** technologies only and did not investigate any aspect of the costs of developing and implementing the SVS technologies, the Program's participants identified and investigated all technical and certification issues in sufficient depth to conclude that there are no insurmountable operational or technical or certification obstacles to implementation of the SVS capability.

It remains for potential users to establish carefully validated operational requirements for low visibility operations from which cost effective functional and system requirements can be established.

The SVS Technology Demonstration Program has caused the user industry, the manufacturing industry and the regulators to become aware of the potential of SVS technologies for substantial operational, economic and safety improvements. Substantial research is now required to establish adequate models of low visibility conditions and sensor phenomenology with which to examine alternative sensor technologies, to examine alternative system concepts with which to satisfy the user's operational requirements in the most cost effective manner, and to establish the relationship of SVS technology to other technologies such as GPS in meeting those operational requirements. Probably the most difficult challenge to industry is in performing the necessary economic studies with sufficient depth to fully understand the true costs and benefits of the many technology options.

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